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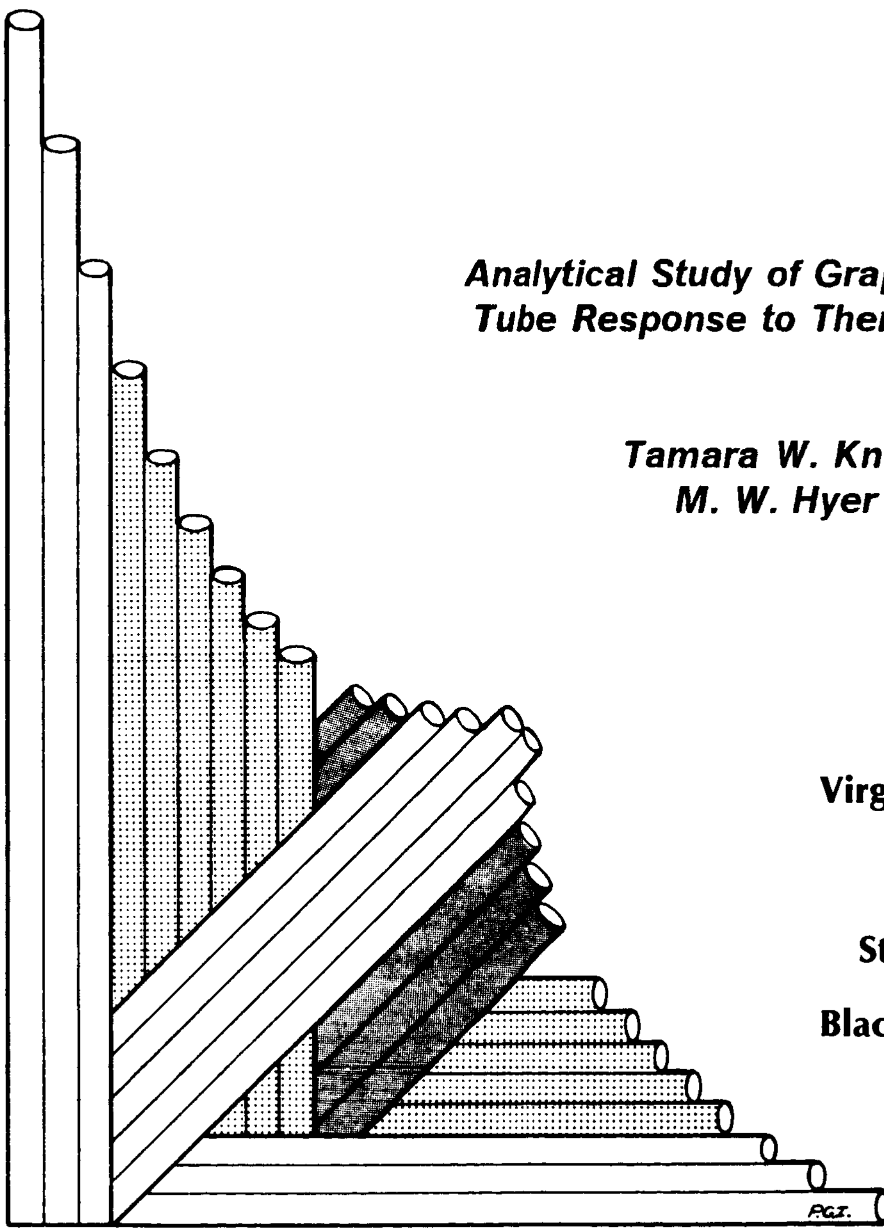

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Abstract

The thermally-induced stresses and deformations in graphite-epoxy tubes with aluminum foil bonded to both the inner and outer surfaces, and to the outer surface only are computed. Tubes fabricated from three material systems, T300/934, P75s/934, and P75s/BP907, and having a 1 inch inner radius and a lamination sequence of $[+15/0/\pm 10/0/-15]_s$ are studied. Radial, axial, and circumferential stresses in the various layers of the tube, in the foil, and in the adhesive bonding the foil to the tubes are computed using an elasticity solution. The results indicate that the coatings have no detrimental effect on the stress state in the tube, particularly those stresses that lead to microcracking. The addition of the aluminum foil does, however, significantly influence the axial expansion of the T300/934 tube, the tube with the softer graphite-fibers. The addition of foil can change the sign of the axial coefficient of thermal expansion. Twist tendencies of the tubes are slightly affected by the addition of the coatings, but are of second order compared to the axial response.

Introduction

This study examines the effect of the thickness of an adhesive layer, used to bond an aluminum foil to the surface of a graphite-epoxy tube, on the thermal response and stress state in the tube. Composite tubes with a balanced symmetric lamination sequence of $[+15/0/\pm 10/0/-15]_s$ and a 1 inch inner radius and 60 mil wall thickness are studied. Three material systems, T300/934, P75s/934, and P75s/BP907, with fiber volume fractions of 68%, 55%, and 55% respectively, are considered. The foil is a 2 mil thick 0 temper 1100 aluminum, and the adhesive is American Cyanamid FM73. The thickness of the adhesive is varied between 0 and 10 mils. The foil is applied to either the inner and outer surface of the tube, or to just the outer surface. The tube is co-cured with the adhesive and foil at 350° F and is assumed to be stress free at that temperature. The tube response is examined at temperatures of -150° F, 0° F, and 150° F.

Of specific interest in the study is the effect of the adhesive layer thickness on the stresses that cause microcracking in the tube, and on the stresses in the foil layer. In addition, the effect on the overall thermal expansion is examined. To better understand the mechanisms controlling the stress states, not only are tubes with aluminum foil and adhesive examined, but also tubes with only adhesive. The elasticity approach developed by Cohen and Hyer [1], and expanded by Rousseau and Hyer [2], is used to study the stresses and deformations. The elasticity approach assumes the problem is axisymmetric and the answers are valid in the central region of the tube, away from any end attachments. Due to the fact that the tube with coatings only on the outer surface constitutes an unsymmetric laminate, the twist response of the tube is also examined.

Results

Thermally-induced stresses in the tubes

The stress state in the composite tube with no foil or adhesive is studied initially. This is referred to as the uncoated tube and it serves as somewhat of a datum. Then tubes with foil and varying thicknesses of adhesive are studied. The thickness of the aluminum layer used is 2 mils in all cases. Adhesive layer thicknesses of 0 mils, 2 mils, 5 mils, and 10 mils are studied. Tubes coated with adhesive, in the thickness described above, but with no aluminum foil are also examined. In the following discussion only the results at a temperature of -150°F are presented. The trends in the stresses at the other temperatures are the same, the magnitudes being proportionately closer to zero at the higher temperatures.

The material properties used in the calculations to represent the three material systems are given in Table 1. The composite materials are assumed to be transversely isotropic in the 2-3 plane. The next sections describe the stresses in the tubes for the three material systems. Results are discussed first for the tubes with coatings on both the inner and outer surfaces, and then for tubes with coatings on the outer surface only. The stress distributions resulting from the addition of the different adhesive thicknesses with and without foil to a given tube are depicted in a single graph to allow direct comparison of the effect of the various coatings. The radial variation of the stresses in the walls of the tubes coated on both the inner and outer surfaces are presented in Figures 1a-7c. The stress distributions in the tubes coated on the outer surface only are presented in Figures 8a-14c. The key maximum values in the various layers, and in the foil and adhesive, are presented in Tables 2-7. Tables 2, 3, and 4 summarize the results for the tubes with coatings on the inner and outer surface, while Tables 5, 6, and 7 summarize the results for tubes with coatings only on the outer surface. The tables will not be referred to specifically in the sections that follow, but it is easy to follow the table entries from the discussion. Herein, the 1-2-3 principal material system is used to describe the stresses in the tube itself, 1 being the fiber direction and 2 being transverse to the fiber direction, in the plane of the layer. The 3 and radial directions are coincident. The stresses in the isotropic materials, namely, the aluminum foil and the adhesive, are described in terms of the axial and circumferential stresses, which are for all intents and purposes principal stresses, though not necessarily the maximum and minimum ones. The maximum shear stresses in the layers are also presented in the tables.

Stresses in tubes coated on the inner and outer surfaces

The fiber direction stresses in the composite and axial stresses in the foil and adhesive as a function of radial position are shown in Figs. 1a, 1b, and 1c for the three material systems. In these and subsequent figures, the nondimensional radial distance through the tube wall is on the horizontal axis. Stresses are on the vertical axis. The nondimensional radial location at zero corresponds to the inner radius of the composite tube. The nondimensional radius unity corresponds to the outer radius of the tube. Stresses in the adhesive and foil are given by the stresses at radial location less than zero and greater than unity. Shown on each figure are the stresses for the case of no foil or adhesive (uncoated tube); the case of foil with no adhesive; cases with no foil but several thicknesses of adhesive; and cases of foil with several thicknesses of adhesive. The leftmost and rightmost positions on the horizontal axis, then, correspond to stresses in the foil, stresses in the adhesive, or stresses at the extreme radial locations in the tube itself, depending on the particular case and the particular figure.

As can be seen in Figs. 1a, 1b, and 1c, the axial stress in the foil is not a strong function of the material system, nor adhesive thickness. The values are between 60 and 70 ksi for all cases. Nor are the axial stresses in the adhesive a strong function of material system or adhesive thickness, the values ranging from 7-8 ksi for all cases. The stresses in the composite tube, however, are definitely a function of the material system. The stresses in the fiber direction in the P75s/BP907 tube are approximately twice the stresses in the T300/934 tube. This is attributed to the material properties of the tube itself, and is not related to the foil or adhesive. Figures 2a, 2b, and 2c provide details of the stresses parallel to the fibers in just the composite. In figures such as these that are used to show the details of the stresses within the composite tube itself, the vertical scale has been reduced and stresses in the foil and adhesive eliminated from the plot. The above-mentioned sensitivity of the tube stresses to the material system is more evident in these figures. In addition, the sensitivity to the different thicknesses of adhesive is also evident. For the case of P75s/BP907, Fig. 2c, there is little influence of the foil and adhesive on the fiber direction stresses. This is evidenced by the fact that all cases are grouped closely to each other in that figure. On the other hand, for T300/934, Fig. 2a, there is significant spread to the results. It is noted that for all three material systems and all adhesive layer thicknesses, the fiber direction stresses are quite small compared to the failure stress of the material. The addition of foil and adhesive to the inner and outer surface of a composite tube, therefore, is not considered detrimental to the stresses in the fiber direction.

Whereas in the axial direction the stresses in the foil and adhesive were not a functions of material system, it is seen from Figures 3a, 3b, and 3c that the circumferential stresses in the foil are a strong function of the material system. For the T300/934 tube at -150° F, Fig. 3a, the foil is in tension in the circumferential direction. In contrast, in the P75s/934 tube, Fig. 3b, the foil is in compression in the circumferential direction, and for the P75s/BP907 tube, Fig. 3c, the foil is in even greater compression in the circumferential direction. The sign change in the circumferential stress as the material system is changed is directly related to the magnitude of the coefficient of thermal expansion of a layer of composite material perpendicular to the fiber, i.e., α_2. A compressive stress in the foil could lead to wrinkling if the adhesive bond is poor, while a tensile stress in the foil could cause tearing. It should be noted that the circumferential stress in the adhesive is tensile, independent of material system, and ranges from 2 to 5 ksi.

Figures 4a, 4b, and 4c provide details of the stresses transverse to the fibers in the layers of the composite tube. The influence of the foil and the various thickness of adhesive on the transverse stress, one of the stress components which cause microcracking, is a strong function of material system. For T300/934, Fig. 4a, the addition of foil and adhesive in any thickness, including the case of zero adhesive thickness, tends to force the transverse stress to be less tensile. For some cases with this material system the transverse stresses are actually compressive, this being beneficial for reducing microcracking. For the P75s/934, Fig. 4b, the addition of foil with no adhesive causes a small additional amount of tension in the transverse direction. However, including an adhesive layer with the foil causes the transverse stresses to be less tensile. With the P75s/BP907, Fig. 4c, the addition of foil causes transverse stresses to approximately double. The addition of an adhesive layer causes variations in this increase, the thicker adhesive with foil causing a less severe stress increase. In Fig. 4c there are two distinct sets of data. One set, the upper one, is the case of the tube with adhesive and foil. The lower set is the case of the tube with adhesive only. Considering all three material systems and all cases of adhesive thicknesses, there is no condition when the transverse stresses become severe.

The shear stresses in the tube, Figs. 5a, 5b, and 5c, are practically independent on whether or not there is a foil and or adhesive coating. This is indicated by the small variations in the shear stress distributions for the different cases of foil and adhesive coatings shown in each of the figures. The shear stresses do, however, increase with the addition of foil and/or adhesive. The shear stress values for the foil and adhesive are one half the maximum difference in the principal stresses. For this problem, the three principal stresses in the foil are, for all intents and purposes, coincident with the axial, circumferential, and radial directions. For all material systems, the maximum principal stress in the foil is the axial stress. For the P75s/934 and P75s/BP907 systems the minimum principal stress in the foil is coincident with the circumferential direction. For the T300/934 system the minimum principal stress in the foil is radial. As can be seen, the maximum shear stress in the foil is dependent on the material system, ranging from 27 to 45 ksi. Figures 6a, 6b, and 6c show details of the shear stress in the tube itself. Except for the two distinct groups of data for the P75s/BP907, the figures demonstrate the rather weak dependence of shear stress in the tube itself on the existence of coatings. Although the shear stress reaches 4000 psi in the P75s/BP907 tube, the highest shear stress in the three material systems, this stress is below expected failure levels.

The radial stresses, though small, are strongly dependent on material system and on the addition of foil and adhesive layers. The radial stress distribution in the uncoated tube is very similar for all three material systems. This can be seen by examining the solid lines in each of Figures 7a, 7b, and 7c. The addition of foil and adhesive to the T300/934 tube, however, has the opposite effect to adding the foil and adhesive to the P75s/BP907 tube. The radial stress between the foil and adhesive is tensile near the outer radius in the P75s/BP907 system, Fig. 7c, while in the T300/934 system, Fig. 7a, that stress is compressive. This difference was also reflected in the sign of the circumferential stress in the foil in these two systems. The difference can be explained as follows: When cooled, the P75s/BP907 shrinks radially more than the foil. At the outer radius the tube wants to pull away from the foil, and at the inner radius it wants to close in on the foil. The pulling away of the tube from the foil at the outer radius causes a tensile σ_r at the outer interface. The closing in at the inner radius causes radial compression at the inner interface. At both locations the radial stresses cause compressive circumferential stresses in the foil. In contrast, the T300/934 does not shrink as much radially as the foil. Therefore at the outer radius the foil closes in on the tube, while at the inner radius the foil pulls away from the tube. This results in tensile σ_r at the inner interface and compressive σ_r at the outer interface. These both cause tensile circumferential stresses in the foil.

In summary, the calculations indicate that the addition of foil and any thickness of adhesive is not detrimental to either the fiber direction or transverse stresses. The transverse stresses, which together with the shear stresses, are responsible for microcracking in general decrease with the addition of coatings to a composite tube for all of the material systems studied. The shear stresses, on the other hand, increase slightly in all three material systems. On balance, it is felt the addition of foil and adhesive have no detrimental effect on the stresses that cause microcracking in the plane of the lamina. The addition of foil and adhesive also influence the interlaminar radial stresses. Although the interlaminar tensile stresses are not large in any of the material systems, the addition of foil and adhesive increases these stresses in some locations of the tube. If the interlaminar bonds between layers of the composite, or between foil and adhesive, or between adhesive and composite are quite weak, these interlaminar stresses could cause separation.

It should be mentioned that the stresses in the foil are quite high. The stresses are beyond the yield stress of 0 temper 1100 aluminum. Therefore these results, which are based on a linear elastic analysis, would be in question. If a 7000 series aluminum foil was used the stresses in the foil may be within the linear elastic range. However, any yielding of the foil would decrease its stiffness and thereby decrease its influence on the tube itself. Not including yielding of the foil material, if it actually would occur, results in conservative calculations of the influence of the foil.

Tables 2, 3, and 4 summarize the maximum values of the fiber direction, transverse, shear and radial stresses. Remember that in the isotropic adhesive layer and foil, σ_1 is the axial stress, σ_2 the circumferential stress, and τ_{12} the maximum shear stress. As can be seen from the previous figures, except for the radial stress component, all stresses are practically constant within a layer. Therefore the maximums reported in Tables 2, 3, and 4 are essentially the value of the particular stress component within the layer.

Stresses in tubes coated on the outer surface only

Coatings on the outer surface of the tube only have similar effects on the stresses in the aluminum, adhesive, and tube as coatings on both surfaces. Within the composite the variation of the stresses caused by the different coatings is less than in the tube coated on both surfaces. Stresses in the foil and adhesive are roughly the same in corresponding coating types regardless of whether the coatings are on both the inner and outer surface, or on the outer surface only. As with the coatings on the inner and outer surface, the radial stress distributions are greatly affected by the material system. Figures 8a-14c illustrate these results. Tables 5, 6, and 7 summarize the results, as did Tables 2, 3, and 4 for tubes with coatings on both inside and outside. By comparing Tables 5, 6, and 7 with Tables 2, 3, and 4, it can be seen that relative to the uncoated tube, the addition of coatings on just the outside has less of an effect on stresses than the addition of coatings on both the inside and outside. Therefore, it can be concluded that the addition of an aluminum foil and adhesive coating to only the outer surface of the composite is not detrimental to the stresses in the tube.

Thermally-induced deformations in the tubes

Accompanying any temperature change are deformations in the axial, circumferential, and radial directions. Unless clearance near the inner or outer radius of the tube is an issue, radial deformations are not critical. (An exception to this is at the ends of the tube where a mismatch in the radial deformations of the tube and the radial deformation of any end connectors could lead to severe stresses.) Here the effects of the coatings on the axial and circumferential deformations of the tube are discussed. The circumferential deformations are examined in the context of twisting of the tube.

Axial extension of the tubes

The axial extension of the tubes coated on both the inner and outer surface are graphically presented in Figures 15a, 15b, and 15c. For tubes coated on the outer surface only the extensions are presented in Figures 16a, 16b, and 16c. The results are presented as the thermally induced axial strain as a function of tube temperature, zero strain corresponding to the 350° F processing temperature. The numerical results for the axial extension and the thermally induced twist to be discussed shortly, for all coatings are summarized in Tables 8, 9, and 10.

As can be seen from the results, the axial response of the uncoated tube for all three material systems is extensional. Of course the axial response is maximum at -150° F. The addition of foil with any thickness of adhesive to the T300/934 tube changes this characteristic and causes an axial contraction that is maximum at -150° F. A coating of adhesive only on the T300/934 tube decreases the amount of axial response relative to the uncoated tube but does not change its sign. The addition of a coating of foil and/or adhesive to the P75s/934 or P75s/BP907 tubes decreases the axial response but does not change its sign. The thickness of the adhesive layer does not have a significant effect on the axial deformations of these two material systems.

For tubes coated on the outer surface only, the axial response is positive for all three material systems. For the T300/934 tube, one foil is not enough to reverse the effects of the tube itself. In all cases, the coefficient of thermal expansion is decreased by less than with the coatings on both surfaces. A comment should be made at this time regarding thermally-induced axial expansion. The axial expansion, or contraction as the case may be, is a function of the elastic properties and thermal expansion properties of the graphite-epoxy, the adhesive, and the aluminum. The elastic and thermal expansion properties in the axial direction are important, but Poisson's ratio also has a role. For example, when a tube is subjected to a radial stress, due to the Poisson effect its length changes. A circumferential stress will also contribute to a length change. The difference in material properties between the graphite-epoxy tube and the aluminum and adhesive, coupled with the temperature change, changes the radial and circumferential stresses in the tube, and induces radial and circumferential stresses in the adhesive and foil. Indirectly, these radial and circumferential stresses influence the axial deformation of the tube. These are important enough effects that thinking of the tube as strictly an axial element can lead to the wrong conclusions.

Thermally-induced twist

The thermally-induced twist in the tube with and without coatings is very small. To be sure it is not zero, but because the tubes are balanced, twist tendencies are of second order compared to axial extension characteristics. However, since the off axis layers at $+\theta$ are at a slightly different radial position than the off axis layers at $-\theta$ (θ here being 10° or 15°), there is a twist. Twist as a function of temperature is shown in Figs. 17a-18c. A summary of the results is presented in Tables 8-10. The figures show the twist of the tubes, in microradians per inch, as a function of temperature.

An examination of the twist data reveals an unexpected effect. The addition of a coating, be it foil or adhesive or both, increases the twist tendency relative to the uncoated tube in both the T300/934 and P75s/934 material systems. This despite the fact that foil and adhesive are each isotropic and by themselves have no tendency whatsoever to twist. The increased twist with the addition of the coatings is again due to coupling of radial, circumferential, and axial response. This is as follows: With no coating, the tube does twist, due to the aforementioned difference in radial location of the $+\theta$ and $-\theta$ layers. One can think of the tube as then having some net slight off-axis fiber orientation causing a small amount of twist as the tube is cooled. If a radial stress is applied to the tube, at either the inner or outer surface, the radius changes and accordingly, the circumference changes. The change in circumference results in a circumferential strain which, through shear-extension coupling of the slightly off-axis material, causes twist. Therefore, anything influencing the radial stresses, and hence the circumferential stresses, as the various coatings do, influences the twist. While the addition of the coatings influences all three material systems, the additions influence the P75s/BP907 material system the least. How much the coatings influence the twist, and indeed the axial extension discussed above, is a function of all the material properties. From the study here, it also appears that the coefficients of thermal expansion of the graphite epoxy have a strong influence, particularly in the presence of the stiffer P75s fibers.

A coating applied only to the outer surface of the tube has a similar but weaker effect on the twist than that caused by coatings on both surfaces.

As mentioned above the units of twist in the figures and tables are radians/unit length of tube in inches. To determine the twist of the end of a length of tube relative to the other end, multiply the number in the table by the length in inches.

Thermal Expansion Coefficients

The extension and twist data in Tables 8, 9, and 10 can also be presented in terms of the coefficients of thermal expansion (CTE) of the tube. Tables 11, 12, and 13 contain the coefficients of thermal expansion for each of the tube configurations studied. In terms of the quantities determined in the elasticity solution, the coefficients of thermal expansion in the axial direction, the circumferential direction, and the twist coefficient, α_x , α_y, and α_{xy}, respectively, are given by

$$\alpha_x \equiv \frac{\varepsilon^o}{\Delta T}$$

$$\alpha_y \equiv \frac{\Delta C_{mean}/C_{mean}}{\Delta T}$$

$$\alpha_{xy} \equiv \frac{\gamma^o R_{mean}}{\Delta T} .$$

In the above ε^o is the axial strain in the tube due to a temperature change ΔT and γ^o is a measure of shear strain in the tube, also due to temperature change ΔT . C_{mean} is the mean circumference of the tube, and ΔC_{mean} is the change in that mean circumference due to a temperature change. R_{mean} is the mean radius of the tube. Reference 2 explains these variables in detail.

Table 11 reveals the dramatic influence of the coatings on the axial response of the T300/934 tube. With no coating, the axial coefficient of thermal expansion is -0.4×10^{-6}/°F. With foil and 2 mils of adhesive on the inner and outer surfaces, the coefficient changes to 0.088×10^{-6}/°F. With coating on the outer surface only the coefficient is -0.146×10^{-6}/°F. Tables 12 and 13 indicate the smaller influence of coatings on the other material systems. The tables also indicate the change in twist tendencies caused by the addition of the coatings. The use of nanoradians per inch to represent twist reemphasizes the fact that twist is a second order effect.

It is of interest to compute the coefficients of thermal expansion using classical lamination theory. From classical lamination theory the coefficients of thermal expansion can be determined by applying a temperature change and using the resulting midplane strains. For this condition, then, in a symmetric laminate

$$\alpha_x \equiv \frac{\varepsilon_x^o}{\Delta T}$$

$$\alpha_y \equiv \frac{\varepsilon_y^o}{\Delta T}$$

and

$$\alpha_{xy} \equiv \frac{\gamma_{xy}^o}{\Delta T},$$

where ε_x^o, ε_y^o, and γ_{xy}^o are the midplane strains resulting from the temperature change. In an unsymmetric laminate a change in temperature induces curvatures as well as extensions. Thus the above expressions do not hold. Although the tubes coated only on the outer surface constitute an unsymmetric laminate, the CTEs were approximated using classical lamination theory by analyzing a symmetric laminate with half of the thickness of the coating on the top surface, and half on the bottom.

An examination of Tables 11-13 indicates the axial and transverse coefficients of thermal expansion calculated with classical lamination theory are fairly close to those calculated from the elasticity solution for the uncoated tube. Lamination theory, however, does not predict twisting. For tubes coated with foil only, lamination theory predicts the CTEs fairly well. For tubes coated with adhesive only, lamination theory is not as accurate. With foil and adhesive, for increasing adhesive thicknesses the difference between the predictions of CTE of classical lamination theory and the elasticity solution increases.

Conclusions

From the results presented there are two important findings. First, it appears that coatings in any combination of foil or adhesive thickness, and whether on the inside and outside, or just the outside, do not have any detrimental influence on the stress state in the composite tube. Secondly, the coatings do influence the deformations. The addition of coatings can change the axial expansion response, the response of the T300/934 material system being most severely influenced. The tubes all experience twist tendencies but the magnitude of these tendencies is very small. Clearly the tube response is a function of the adhesive layer thickness, but compared to the effect of the foil, changing the thickness of the adhesive does not greatly influence the tube response.

As part of the findings several other interesting results were revealed. The circumferential stresses in the foil were found to be a very strong function of material system. The circumferential stresses in the foil were tensile for the T300/934 system, and compressive for P75s/BP907. This was due to the relative expansion of the foil and the tube in the radial direction. Also revealed was the fact that a significant coupling between radial, circumferential, and axial material properties exists in the tubes. Axial response, particularly deformation, is influenced not only by material properties in the axial direction, but also, response in the other directions, through Poisson's effects.

References

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	T300/934	P75s/934	P75s/BP907	Aluminum	Adhesive
E_1 (Msi)	18.9	42.0	42.0	10.0	0.54
E_2 (Msi)	1.4	0.83	0.83	-	-
ν_{12}	0.31	0.35	0.35	0.30	0.35
G_{12} (Msi)	0.69	0.61	0.61	3.85	0.20
α_1 (10^{-6}/°F)	-0.06	-0.584	-0.584	12.8	21.8
α_2 (10^{-6}/°F)	13.9	19.2	28.8	-	-

Table 1. Material Properties

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-5,100	-9,950	-5,775	-10,500	-11,317	-6,763	-12,650	-8,325
	10°	-430	-5,100	-975	-5,675	-6,270	-1,754	-7,425	-3,050
	0°	3,400	-1,125	2,975	-1,550	-2,146	2,343	-3,175	1,300
	Adhesive	-	-	7,700 [1]	7,500 [1]	7,432 [1]	7,624 [1]	7,350 [1]	7,500 [1]
	Foil	-	67,725 [1]	-	67,150 [1]	66,303 [1]	-	64,975 [1]	-
σ_2	15°	975	225	675	50	-232	255	-650	-375
	10°	725	-25	425	-225	-495	-7	-925	-650
	0°	525	-250	225	-450	-710	-233	-1,150	-875
	Adhesive	-	-	4,900 [2]	4,625 [2]	4,500 [2]	4,723 [2]	4,300 [2]	4,475 [2]
	Foil	-	13,275 [2]	-	11,950 [2]	10,080 [2]	-	7,200 [2]	-
τ_{12}	15°	2,350	2,450	2,425	2,500	2,541	2,523	2,650	2,675
	10°	1,600	1,675	1,675	1,700	1,736	1,725	1,800	1,825
	0°	0.26	0.27	0.27	0.28	0.29	0.28	0.29	0.28
	Adhesive	-	-	3,850 [3]	3,750 [3]	3,716 [3]	3,812 [3]	3,675 [3]	3,750 [3]
	Foil	-	33,863 [3]	-	33,575 [3]	33,152 [3]	-	32,488 [3]	-
σ_r	Tube	0/+15[4] 3.9	+15/0 18.0	0/+10 5.9	+15/0 23.4	+15/0 31.3	+15/0 16.1	+15/0 43.5	+15/0 33.0
	Coating	-	foil/15 26.0	adh/15 9.7	adh/15 33.1 foil/adh 23.9	adh/15 42.6 foil/adh 20.3	adh/15 23.5	adh/15 57.5 foil/adh 14.5	adh/15 44.4

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs

Table 2. Maximum Stresses in T300/934 Tubes with Coatings on the Inner and Outer Surfaces at -150 ° F

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-14,466	-18,716	-15,339	-19,391	-20,379	-16,577	-21,964	-18,487
	10°	-230	-4,946	-734	-5,415	-6,115	-1,479	-7,264	-2,693
	0°	11,400	6,302	11,207	6,005	5,549	10,879	4,763	10,250
	Adhesive	-	-	7,493 [1]	7,457 [1]	7,432 [1]	7,417 [1]	7,357 [1]	7,308 [1]
	Foil	-	68,533 [1]	-	68,022 [1]	67,291 [1]	-	66,160 [1]	-
σ_2	15°	1,253	1,368	1,043	1,246	1,073	759	811	356
	10°	1,057	1,177	844	1,053	878	555	611	146
	0°	912	1,037	693	911	731	397	459	-36
	Adhesive	-	-	3,739 [2]	3,900 [2]	3,780 [2]	3,531 [2]	3,596 [2]	3,236 [2]
	Foil	-	-464 [2]	-	-2,226 [2]	-4,715 [2]	-	-8,496 [2]	-
τ_{12}	15°	2,815	2,722	2,888	2,763	2,821	2,987	2,908	3,129
	10°	1,922	1,858	1,973	1,887	1,926	2,042	1,988	2,140
	0°	0.312	0.319	0.313	0.321	0.323	0.315	0.327	0.321
	Adhesive	-	-	3,747 [3]	3,729 [3]	3,716 [3]	3,709 [3]	3,679 [3]	3,654 [3]
	Foil	-	34,498 [3]	-	35,124 [3]	36,053 [3]	-	37,328 [3]	-
σ_r	Tube	0/-15[4] 6.6	0/-15 8.4	0/-15 7.9	0/-15 9.5	0/-15 11.2	0/+10 10.1	0/+10 14.9	+15/0 19.7
	Coating	-	foil/15 1.31	adh/15 7.5	adh/15 6.1 adh/foil 4.2	adh/15 12.9 adh/foil 8.9	adh/15 17.6	adh/15 23.4 adh/foil 15.9	adh/15 32.2

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs

Table 3. Maximum Stresses in P75s/934 Tubes with Coatings on the Inner and Outer Surfaces at -150 ° F

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-21,488	-22,415	-22,031	-22,986	-23,825	-22,826	-25,186	-24,105
	10°	-344	-4,634	-799	-5,103	-5,777	-1,479	-6,892	-2,601
	0°	16,931	9,795	16,550	9,442	8,907	15,969	8,000	14,980
	Adhesive	-	-	6,680 [1]	7,014 [1]	6,981 [1]	6,653 [1]	6,929 [1]	6,612 [1]
	Foil	-	61,698 [1]	-	61,346 [1]	60,841 [1]	-	60,052 [1]	-
σ_2	15°	1,862	3,538	1,802	3,463	3,356	1,722	3,195	1,607
	10°	1,571	3,278	1,512	3,202	3,094	1,429	2,930	1,313
	0°	1,356	3,110	1,294	3,032	2,922	1,211	2,754	1,092
	Adhesive	-	-	1,227 [2]	2,514 [2]	2,440 [2]	1,169 [2]	2,328 [2]	1,087 [2]
	Foil	-	-27,645 [2]	-	-28,726 [2]	-30,252 [2]	-	-32,569 [2]	-
τ_{12}	15°	4,181	3,505	4,199	3,528	3,561	4,222	3,611	4,253
	10°	2,855	2,387	2,868	2,403	2,426	2,888	2,460	2,906
	0°	0.460	0.458	0.465	0.459	0.460	0.467	0.462	0.470
	Adhesive	-	-	3,340 [3]	3,507 [3]	3,491 [3]	3,327 [3]	3,465 [3]	3,306 [3]
	Foil	-	44,671 [3]	-	44,527 [3]	45,017 [3]	-	45,729 [3]	-
σ_r	Tube	0/-15[4] 9.7	0/+15 53.0	0/-15 10.3	0/+15 51.2	0/+15 48.5	0/-15 11.1	0/+15 44.5	0/-15 12.28
	Coating	-	15/foil 52.2	adh/15 2.5	15/adh 49.8 adh/foil 54.2	15/adh 46.3 adh/foil 56.9	adh/15 5.8	15/adh 41.1 adh/foil 60.9	adh/15 10.8

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs

Table 4. Maximum Stresses in P75s/BP907 Tubes with Coatings on the Inner and Outer Surfaces at -150 ° F

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-5,100	-7,700	-5,450	-8,000	-8,454	-5,959	-9,200	-6,800
	10°	-430	-2,900	-700	-3,175	-3,545	-1,119	-4,200	-1,800
	0°	3,400	1,025	3,175	800	472	2,848	-75	2,300
	Adhesive	-	-	7,725 [1]	7,575 [1]	7,538 [1]	7,667 [1]	7,475 [1]	7,600 [1]
	Foil	-	69,525 [1]	-	69,125 [1]	69,489 [1]	-	67,500 [1]	-
σ_2	15°	975	525	825	425	255	605	-4	275
	10°	725	275	575	160	-3	348	-275	-1
	0°	525	75	375	-50	-215	141	-475	-225
	Adhesive	-	-	4,925 [2]	4,750 [2]	4,675 [2]	4,835 [2]	4,600 [2]	4,675 [2]
	Foil	-	15,650 [2]	-	14,600 [2]	13,034 [2]	-	10,550 [2]	-
τ_{12}	15°	2,350	2,425	2,400	2,450	2,473	2,440	2,525	2,515
	10°	1,600	1,650	1,650	1,675	1,691	1,669	1,725	1,755
	0°	0.26	0.27	0.27	0.27	0.28	0.27	0.28	0.27
	Adhesive	-	-	3,863 [3]	3,788 [3]	3,769 [3]	3,834 [3]	3,738 [3]	3,800 [3]
	Foil	-	34,763 [3]	-	34,563 [3]	34,745 [3]	-	33,750 [3]	-
σ_r	Tube	0/-15[4] 3.4	+10/0* -24.2	-15/0* -8.4	0/+15* -30.1	0/+15* -39.4	+10/0* -18.5	0/+15* -54.1	0/+15* -37.2
	Coating	-	15/foil* -29.5	15/adh* -9.3	15/adh* -36.5 adh/foil* -27.5	15/adh* -46.6 adh/foil* -24.5	15/adh* -22.8	15/adh* -62.6 adh/foil* -19.7	15/adh* -43.9

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs, * indicates radial stress is every where compressive

Table 5. Maximum Stresses in T300/934 Tubes with Coatings Only on the Outer Surface at -150 ° F

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-14,466	-16,611	-14,910	-16,990	-17,549	-15,557	-18,457	-16,591
	10°	-230	-2,671	-491	-2,924	-3,303	-879	-3,931	-1,520
	0°	11,400	8,715	11,294	8,568	8,341	11,124	7,949	10,815
	Adhesive	-	-	7,498 [1]	7,495 [1]	7,462 [1]	7,454 [1]	7,409 [1]	7,385 [1]
	Foil	-	68,655 [1]	-	68,283 [1]	67,745 [1]	-	66,893 [1]	-
σ_2	15°	1,253	1,342	1,147	1,267	1,159	996	989	765
	10°	1,057	1,149	949	1,073	963	796	791	562
	0°	912	1,008	802	930	817	644	614	405
	Adhesive	-	-	3,758 [2]	3,847 [2]	3,767 [2]	3,645 [2]	3,624 [2]	3,474 [2]
	Foil	-	-858 [2]	-	-2,003 [2]	-3,652 [2]	-	-6,234 [2]	-
τ_{12}	15°	2,815	2,756	2,851	2,781	2,817	2,904	2,873	2,982
	10°	1,922	1,882	1,948	1,899	1,924	1,984	1,963	2,038
	0°	0.312	0.315	0.313	0.316	0.317	0.314	0.319	0.317
	Adhesive	-	-	3,749 [3]	3,748 [3]	3,731 [3]	3,727 [3]	3,705 [3]	3,693 [3]
	Foil	-	34,757 [3]	-	35,143 [3]	35,699 [3]	-	36,564 [3]	-
σ_r	Tube	0/-15[4] 6.6	0/+15 7.8	0/-15 3.5	0/-15 5.5	0/-15 2.3	-15/0* -16.0	-15/0* -19.5	-15/0* -25.5
	Coating	-	15/foil 1.6	15/adh* -7.1	15/adh* -3.5 adh/foil 3.8	15/adh* -10.8 adh/foil 6.8	15/adh* -17.8	15/adh* -22.4 adh/foil 11.6	15/adh* -32.6

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs, * indicates radial stress is everywhere compressive.

Table 6. Maximum Stresses in P75s/934 Tubes with Coatings Only on the Outer Surface at -150 ° F

Stress (psi)	layer	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
σ_1	15°	-21,488	-21,466	-21,764	-21,761	-22,200	-22,173	-22,920	-22,843
	10°	-344	-2,506	-578	-2,746	-3,105	-930	-3,703	-1,515
	0°	16,931	12,939	16,732	12,746	12,454	16,429	11,960	15,916
	Adhesive	-	-	6,660 [1]	6,915 [1]	6,897 [1]	6,645 [1]	6,867 [1]	6,620 [1]
	Foil	-	59,260 [1]	-	59,049 [1]	58,741 [1]	-	58,252 [1]	-
σ_2	15°	1,862	2,977	1,833	2,940	2,887	1,792	2,804	1,729
	10°	1,571	2,706	1,542	2,669	2,615	1,500	2,531	1,436
	0°	1,356	2,522	1,326	2,484	2,429	1,283	2,342	1,218
	Adhesive	-	-	1,164 [2]	1,990 [2]	1,951 [2]	1,135 [2]	1,889 [2]	1,088 [2]
	Foil	-	-35,103 [2]	-	-35,664 [2]	-36,541 [2]	-	-37,808 [2]	-
τ_{12}	15°	4,181	3,744	4,189	3,755	3,771	4,198	3,790	4,219
	10°	2,855	2,553	2,861	2,560	2,571	2,869	2,586	2,881
	0°	0.460	0.459	0.464	0.459	0.460	0.465	0.461	0.466
	Adhesive	-	-	3,330 [3]	3,458 [3]	3,448 [3]	3,322 [3]	3,433 [3]	3,310 [3]
	Foil	-	47,215 [3]	-	47,390 [3]	47,641 [3]	-	48,045 [3]	-
σ_r	Tube	0/-15[4] 9.7	0/+15 69.8	0/-15 8.9	0/+15 67.4	0/+15 63.9	0/-15 7.6	0/+15 58.3	0/-15 5.6
	Coating	-	15/foil 66.3	15/adh* -2.2	15/adh 63.6 adh/foil 67.2	15/adh 59.7 adh/foil 68.6	15/adh* -5.3	15/adh 53.5 adh/foil 70.6	15/adh -10.2

[1] Axial Stress
[2] Circumferential Stress
[3] Maximum Shear Stress
[4] Denotes interface where maximum tension occurs, * indicates radial stress is everywhere compressive

Table 7. Maximum Stresses in P75s/BP907 Tubes with Coatings Only on the Outer Surface at -150 ° F

Coating	result	Temp ° F	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner and outer surface	Ext (μin/in)	-150	200	-25	180	-44	-72	157	-119	110
		0	140	-18	130	-31	-51	110	-83	79
		150	80	-10	74	-19	-29	63	-48	45
	Twist (μrad/in)	-150	0.385	0.402	0.391	0.405	0.411	0.398	0.420	0.410
		0	0.270	0.281	0.273	0.284	0.288	0.279	0.294	0.287
		150	0.154	0.161	0.156	0.162	0.165	0.159	0.168	0.164
outer surface only	Ext (μin/in)	-150	200	83	190	73	59	178	34	160
		0	140	58	130	51	41	125	24	120
		150	80	33	77	29	23	71	13	62
	Twist (μrad/in)	-150	0.385	0.393	0.388	0.395	0.399	0.392	0.403	0.398
		0	0.270	0.275	0.272	0.277	0.279	0.274	0.282	0.279
		150	0.154	0.157	0.155	0.158	0.159	0.157	0.161	0.159

Table 8. Extensions and Twists in T300/934 Tube With Coatings on Inner and Outer Surface, and on Outer Surface Only.

Coating	result	Temp °F	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner and outer surface	Ext (μin/in)	-150	556	433	553	427	418	548	401	536
		0	389	303	387	299	293	383	281	375
		150	222	173	221	171	167	219	161	214
	Twist (μrad/in)	-150	0.485	0.496	0.487	0.499	0.503	0.492	0.510	0.499
		0	0.339	0.347	0.341	0.349	0.352	0.344	0.357	0.349
		150	0.194	0.199	0.195	0.200	0.201	0.197	0.204	0.200
outer surface only	Ext (μin/in)	-150	556	491	554	488	484	551	476	546
		0	389	344	388	342	339	386	333	382
		150	222	196	222	195	193	221	190	218
	Twist (μrad/in)	-150	0.485	0.490	0.486	0.491	0.493	0.488	0.496	0.491
		0	0.339	0.343	0.340	0.344	0.345	0.342	0.347	0.344
		150	0.194	0.196	0.194	0.196	0.197	0.195	0.198	0.197

Table 9. Extensions and Twists in P75s/934 Tube With Coatings on Inner and Outer Surface, and on Outer Surface Only.

Coating	result	Temp ° F	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner and outer surface	Ext (μin/in)	-150	684	500	675	492	480	662	460	640
		0	479	350	473	344	336	464	322	448
		150	274	200	270	197	192	265	184	256
	Twist (μrad/in)	-150	0.721	0.711	0.723	0.713	0.715	0.725	0.719	0.730
		0	0.504	0.498	0.506	0.499	0.500	0.508	0.503	0.511
		150	0.288	0.285	0.289	0.285	0.286	0.290	0.287	0.292
outer surface only	Ext (μin/in)	-150	684	579	679	575	568	673	557	661
		0	479	405	476	402	398	471	390	463
		150	274	232	272	230	227	269	223	264
	Twist (μrad/in)	-150	0.721	0.714	0.722	0.714	0.715	0.723	0.716	0.725
		0	0.504	0.450	0.505	0.500	0.500	0.506	0.501	0.507
		150	0.288	0.285	0.289	0.286	0.286	0.289	0.286	0.290

Table 10. Extensions and Twists in P75s/BP907 Tube With Coatings on Inner and Outer Surface, and on Outer Surface Only.

Coating	result	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner and	α_x ($\mu\varepsilon$/°F)	-0.400[1] (-0.402)[2]	0.050[1] (0.055)[2]	-0.360[1] (-0.392)[2]	0.088[1] (0.061)[2]	0.140[1] (0.070)[2]	-0.310[1] (-0.378)[2]	0.238[1] (0.084)[2]	-0.220[1] (-0.356)[2]
outer	α_y ($\mu\varepsilon$/°F)	13.29[1] (13.28)[2]	14.20[1] (14.20)[2]	13.70[1] (12.93)[2]	14.46[1] (13.95)[2]	14.83[1] (13.58)[2]	14.29[1] (12.44)[2]	15.40[1] (13.01)[2]	15.17[1] (11.70)[2]
surface	α_{xy} (nrad/°F)	0.793[1] (0)[2]	0.828[1] (0)[2]	0.805[1] (0)[2]	0.834[1] (0)[2]	0.847[1] (0)[2]	0.820[1] (0)[2]	0.865[1] (0)[2]	0.845[1] (0)[2]
outer	α_x ($\mu\varepsilon$/°F)	-0.400[1] (-0.402)[2]	-0.166[1] (-0.172)[2]	-0.380[1] (-0.397)[2]	-0.146[1] (-0.168)[2]	-0.120[1] (-0.163)[2]	-0.360[1] (-0.389)[2]	-0.068[1] (-0.153)[2]	-0.320[1] (-0.377)[2]
surface	α_y ($\mu\varepsilon$/°F)	13.29[1] (13.28)[2]	13.83[1] (13.85)[2]	13.49[1] (13.10)[2]	13.98[1] (13.70)[2]	14.20[1] (13.48)[2]	13.79[1] (12.85)[2]	14.55[1] (13.13)[2]	14.27[1] (12.44)[2]
only	α_{xy} (nrad/°F)	0.793[1] (0)[2]	0.810[1] (0)[2]	0.799[1] (0)[2]	0.814[1] (0)[2]	0.821[1] (0)[2]	0.807[1] (0)[2]	0.830[1] (0)[2]	0.820[1] (0)[2]

[1] based on elasticty solution
[2] based on CLT

Table 11. Laminate Coeficients of Expansion for T300/934 Tubes

Coating	result	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner	α_x ($\mu\varepsilon$/°F)	-1.112[1] (-1.111)[2]	-0.866[1] (-0.867)[2]	-1.106[1] (-1.089)[2]	-0.854[1] (-0.854)[2]	-0.836[1] (-0.837)[2]	-1.096[1] (-1.058)[2]	0.802[1] (-0.809)[2]	-1.072[1] (-1.013)[2]
and outer	α_y ($\mu\varepsilon$/°F)	17.26[1] (17.26)[2]	16.89[1] (16.88)[2]	17.77[1] (16.54)[2]	17.18[1] (16.49)[2]	17.60[1] (15.93)[2]	18.46[1] (15.58)[2]	18.23[1] (15.08)[2]	19.44[1] (14.20)[2]
surface	α_{xy} (nrad/°F)	0.997[1] (0)[2]	1.022[1] (0)[2]	1.003[1] (0)[2]	1.028[1] (0)[2]	1.036[1] (0)[2]	1.014[1] (0)[2]	1.051[1] (0)[2]	1.028[1] (0)[2]
outer	α_x ($\mu\varepsilon$/°F)	-1.112[1] (-1.111)[2]	-0.982[1] (-0.987)[2]	-1.108[1] (-1.100)[2]	-0.976[1] (-0.979)[2]	-0.968[1] (-0.967)[2]	-1.102[1] (-1.083)[2]	-0.952[1] (-0.948)[2]	-1.092[1] (-1.058)[2]
surface	α_y ($\mu\varepsilon$/°F)	17.26[1] (17.26)[2]	17.00[1] (17.03)[2]	17.52[1] (16.89)[2]	17.17[1] (16.77)[2]	17.43[1] (16.39)[2]	17.88[1] (16.37)[2]	17.83[1] (15.81)[2]	18.43[1] (15.58)[2]
only	α_{xy} (nrad/°F)	0.997[1] (0)[2]	1.009[1] (0)[2]	1.001[1] (0)[2]	1.011[1] (0)[2]	1.016[1] (0)[2]	1.005[1] (0)[2]	1.022[1] (0)[2]	1.011[1] (0)[2]

[1] based on elasticty solution
[2] based on CLT

Table 12. Laminate Coeficients of Expansion for P75s/934 Tubes

Coating	result	Uncoated Tube	2 mil Foil Only	2 mil Adh Only	2 mil Adh and Foil	5 mil Adh and Foil	5 mil Adh Only	10 mil Adh and Foil	10 mil Adh Only
inner	α_x ($\mu\varepsilon/^{o}F$)	-1.368[1] (-1.368)[2]	-0.999[1] (-0.999)[2]	-1.351[1] (-1.333)[2]	-0.984[1] (-0.983)[2]	-0.960[1] (-0.960)[2]	-1.324[1] (-1.287)[2]	-0.920[1] (-0.926)[2]	-1.279[1] (-1.220)[2]
and outer	α_y ($\mu\varepsilon/^{o}F$)	25.92[1] (25.92)[2]	21.68[1] (21.67)[2]	26.06[1] (24.83)[2]	21.86[1] (21.16)[2]	22.11[1] (20.43)[2]	26.25[1] (23.36)[2]	22.49[1] (19.33)[2]	26.51[1] (21.27)[2]
surface	α_{xy} ($nrad/^{o}F$)	1.485[1] (0)[2]	1.465[1] (0)[2]	1.489[1] (0)[2]	1.468[1] (0)[2]	1.473[1] (0)[2]	1.494[1] (0)[2]	1.480[1] (0)[2]	1.504[1] (0)[2]
outer	α_x ($\mu\varepsilon/^{o}F$)	-1.368[1] (-1.368)[2]	-1.158[1] (-1.163)[2]	-1.359[1] (-1.350)[2]	-1.150[1] (-1.152)[2]	-1.137[1] (-1.136)[2]	-1.345[1] (-1.325)[2]	-1.115[1] (-1.110)[2]	-1.322[1] (-1.287)[2]
surface	α_y ($\mu\varepsilon/^{o}F$)	25.92[1] (25.92)[2]	23.15[1] (23.19)[2]	25.99[1] (25.36)[2]	23.24[1] (22.84)[2]	23.36[1] (22.32)[2]	26.08[1] (24.57)[2]	23.55[1] (21.52)[2]	26.22[1] (23.36)[2]
only	α_{xy} ($nrad/^{o}F$)	1.485[1] (0)[2]	1.470[1] (0)[2]	1.486[1] (0)[2]	1.471[1] (0)[2]	1.473[1] (0)[2]	1.489[1] (0)[2]	1.475[1] (0)[2]	1.493[1] (0)[2]

[1] based on elasticty solution
[2] based on CLT

Table 13. Laminate Coeficients of Expansion for P75s/BP907 Tubes

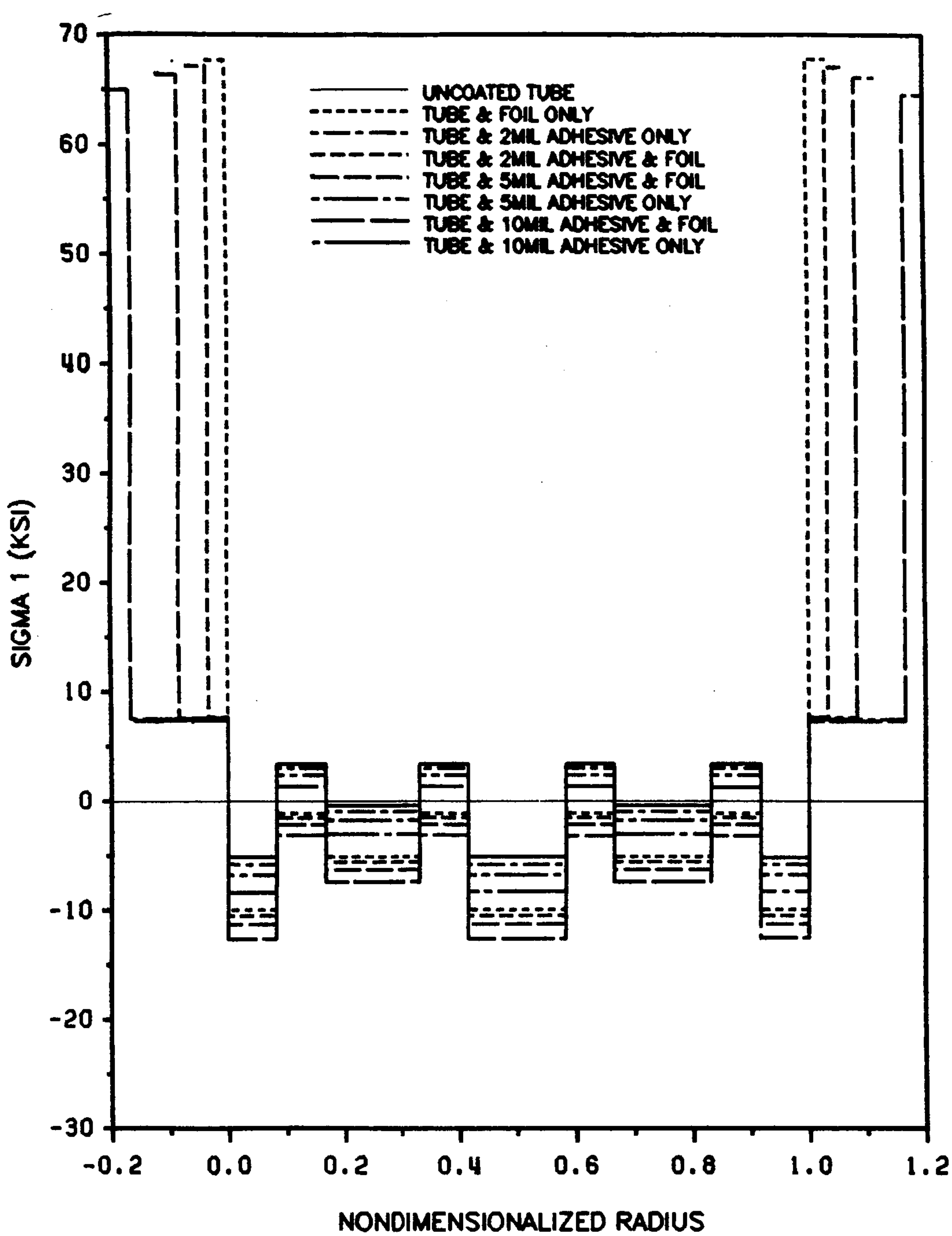

Figure 1a. Fiber Direction and Major Principal Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

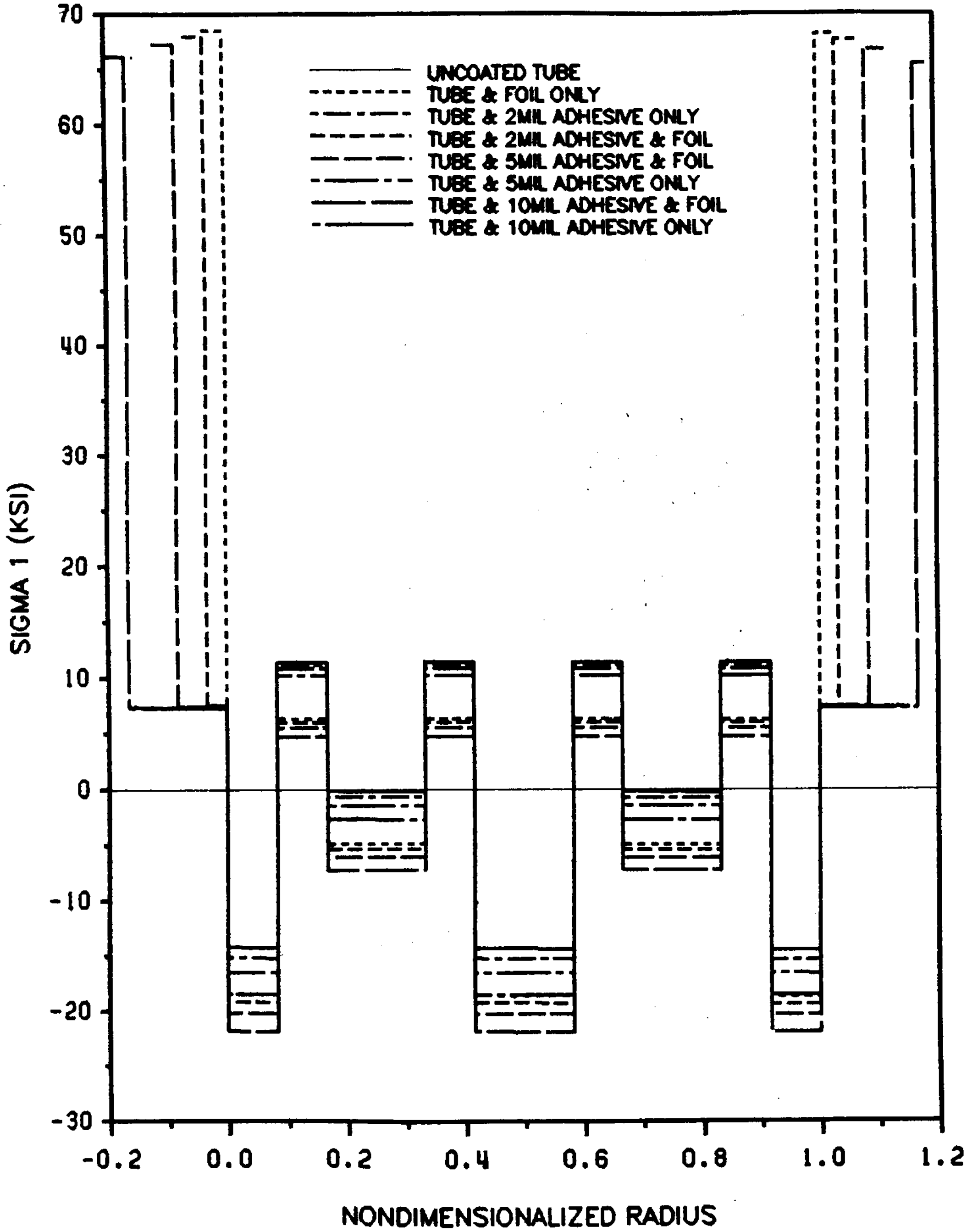

Figure 1b. Fiber Direction and Major Principal Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

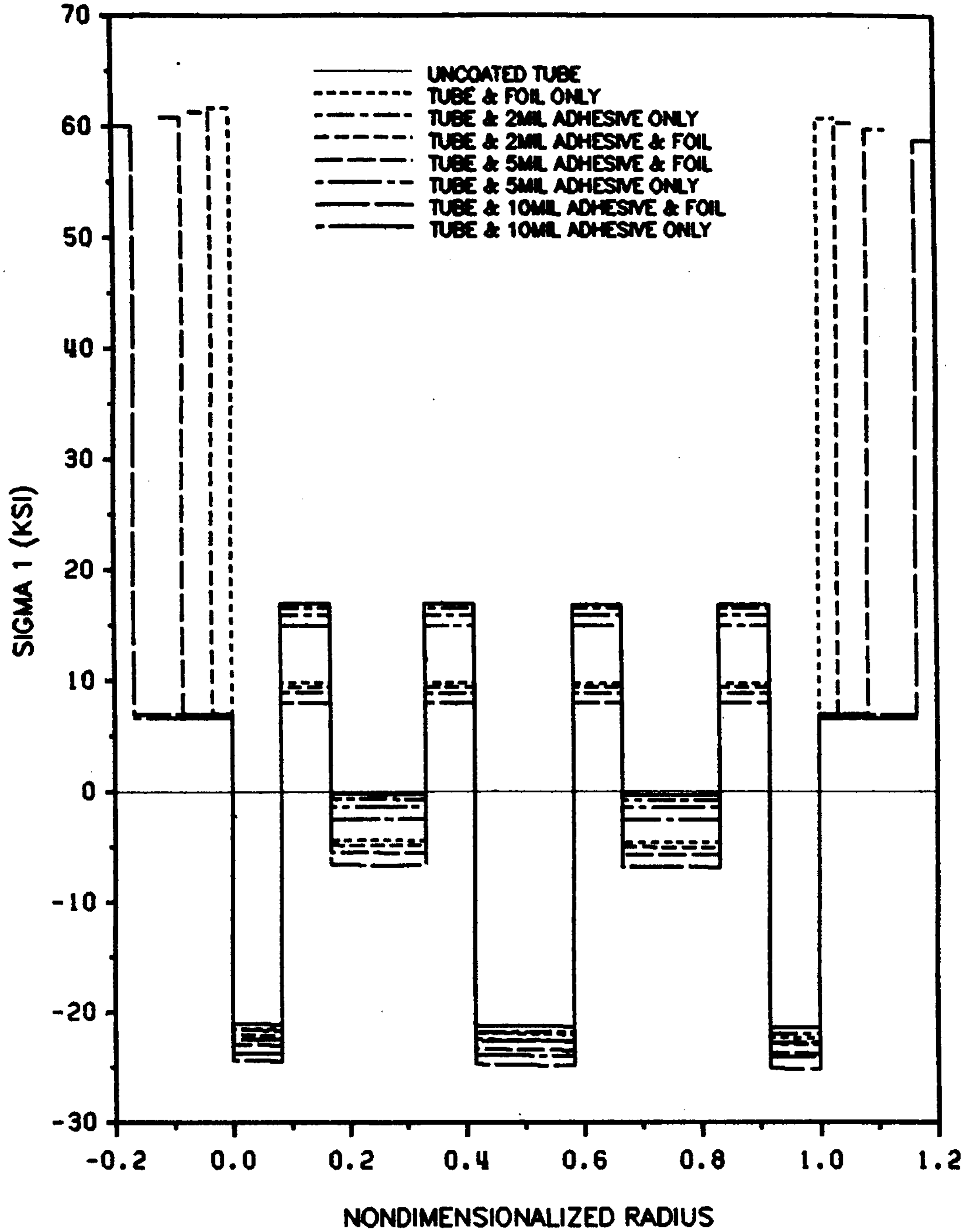

Figure 1c. Fiber Direction and Major Principal Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

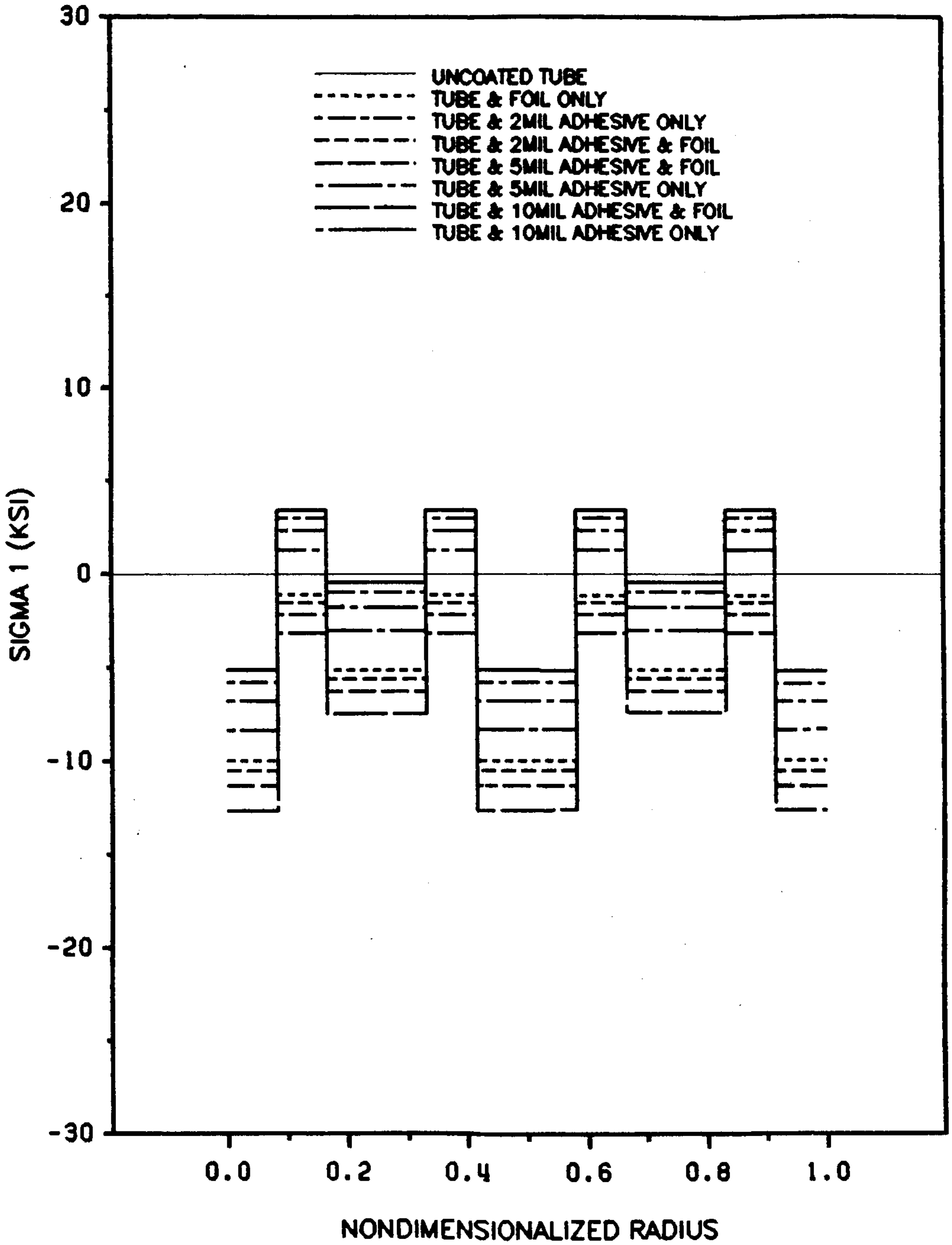

Figure 2a. Details of Fiber Direction Stresses in the T300/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

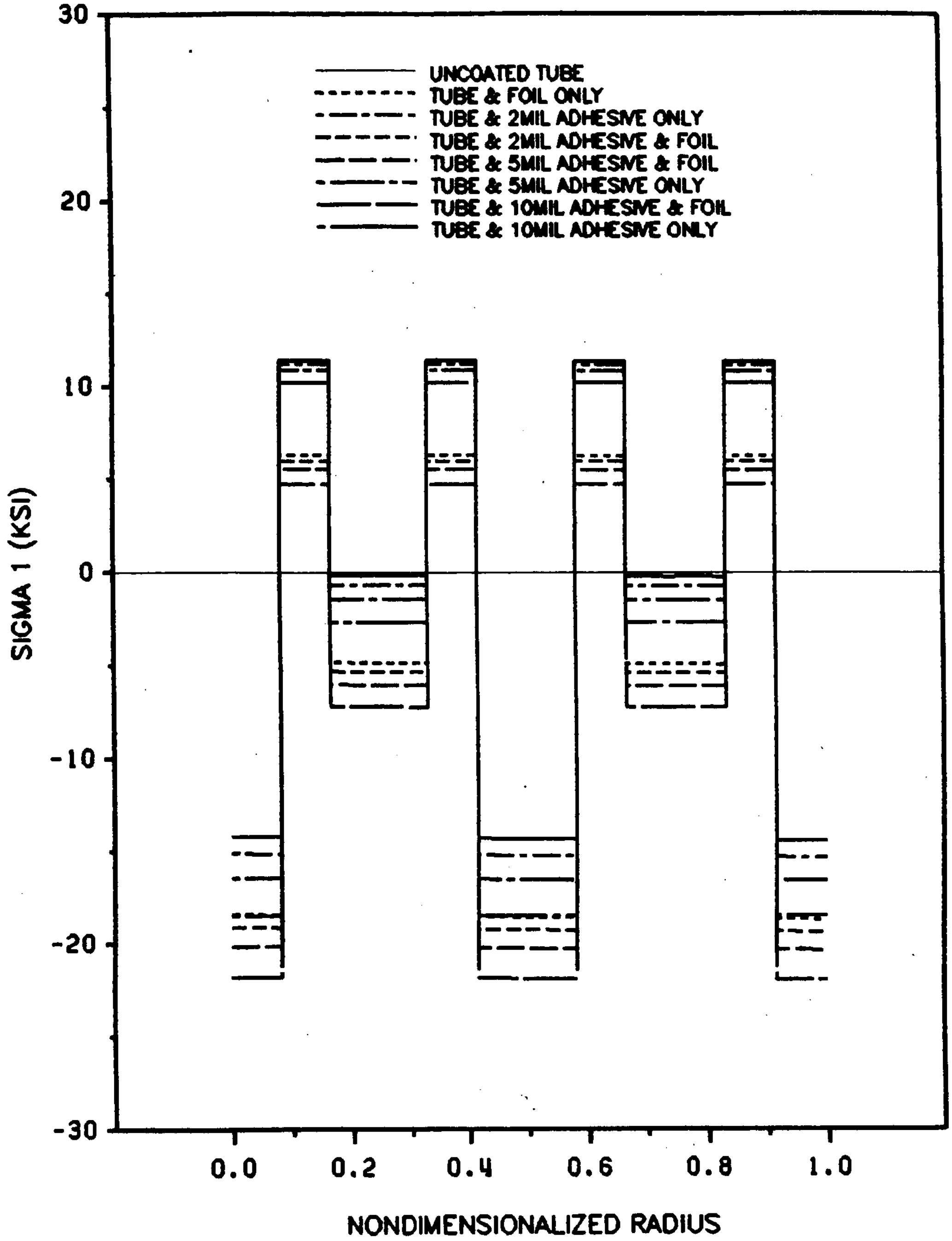

Figure 2b. Details of Fiber Direction Stresses in the P75s/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

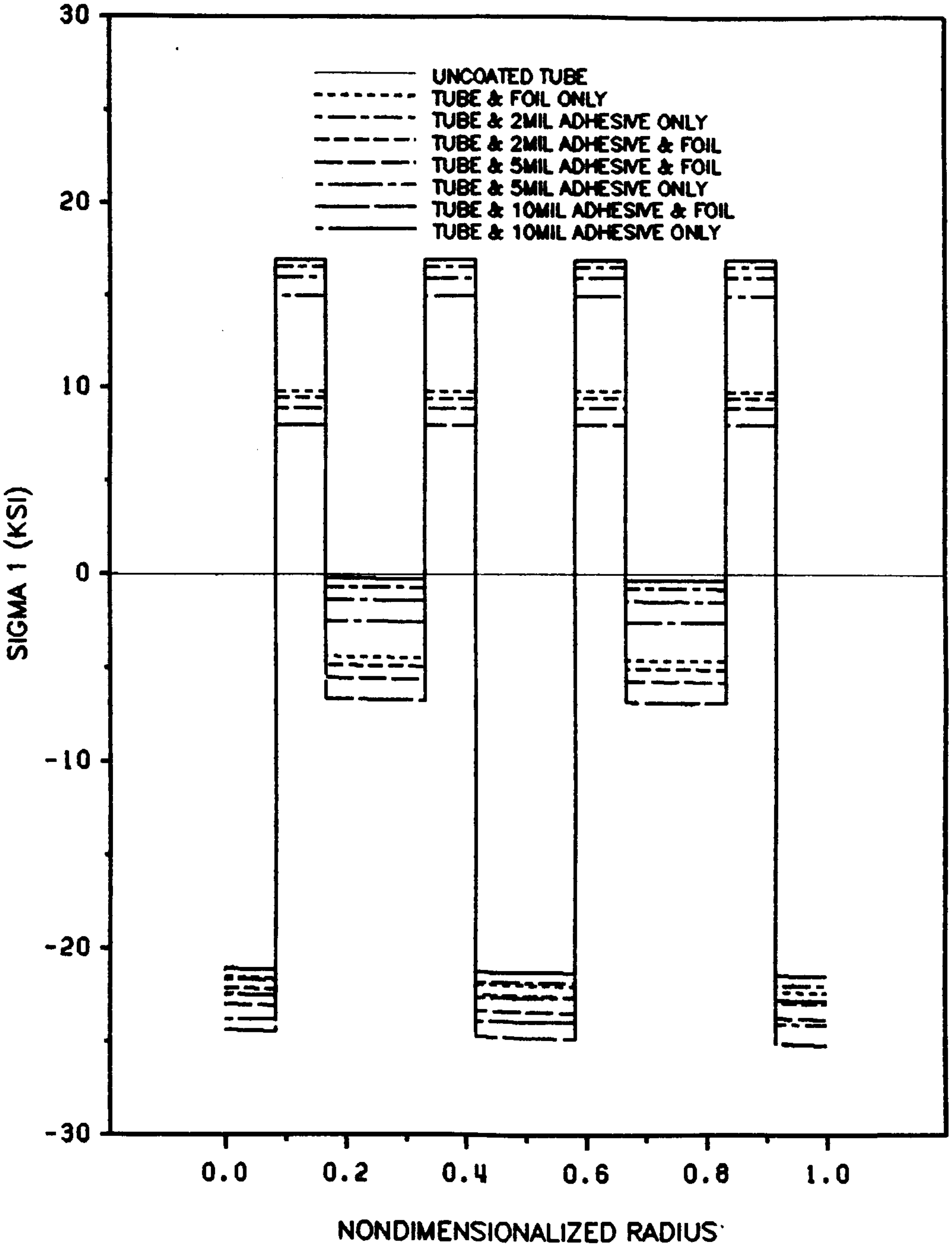

Figure 2c. Details of Fiber Direction Stresses in the P75s/BP907 Tube at -150° F: Coatings on Inner and Outer Surfaces.

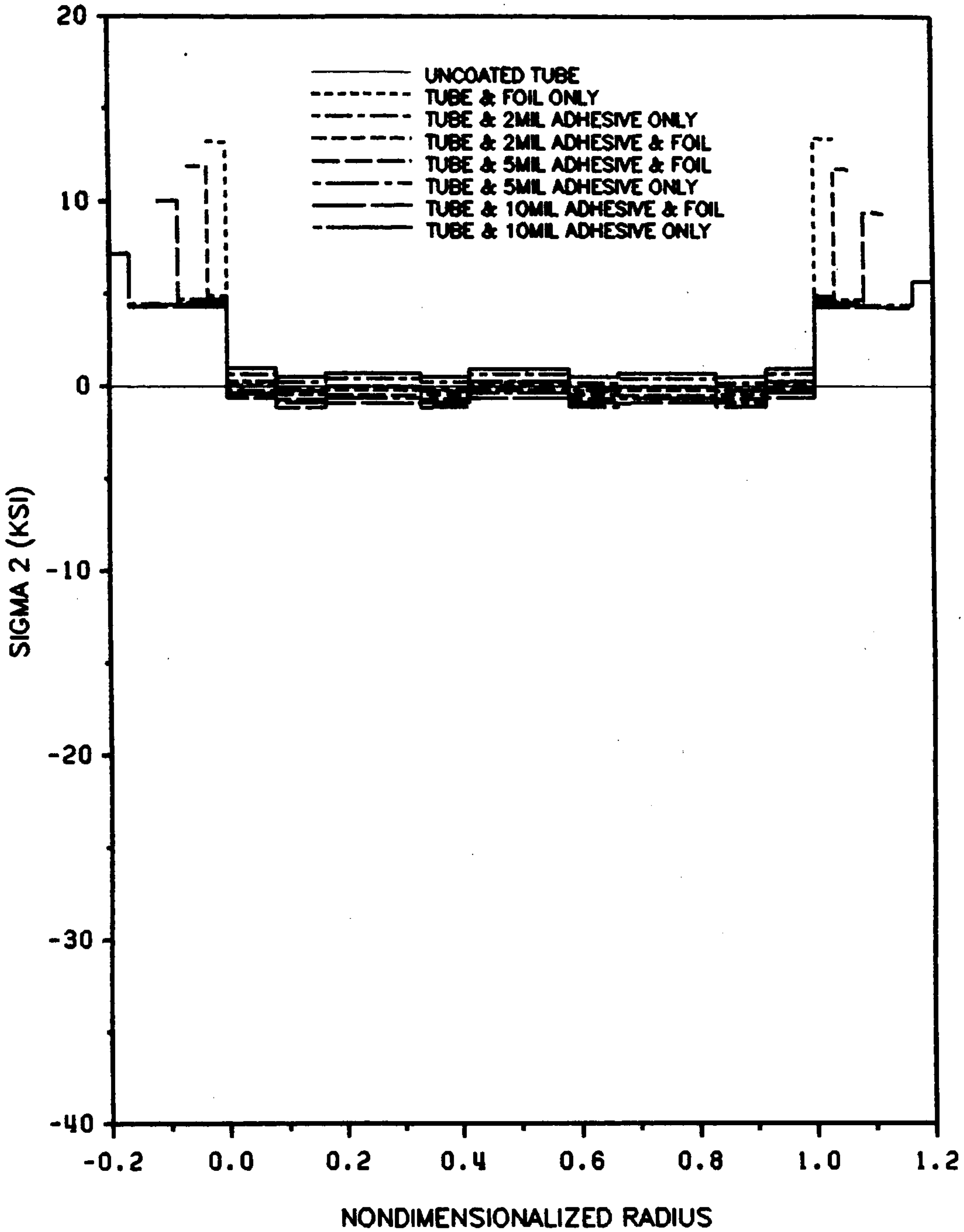

Figure 3a. Transverse and Minor Principal Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

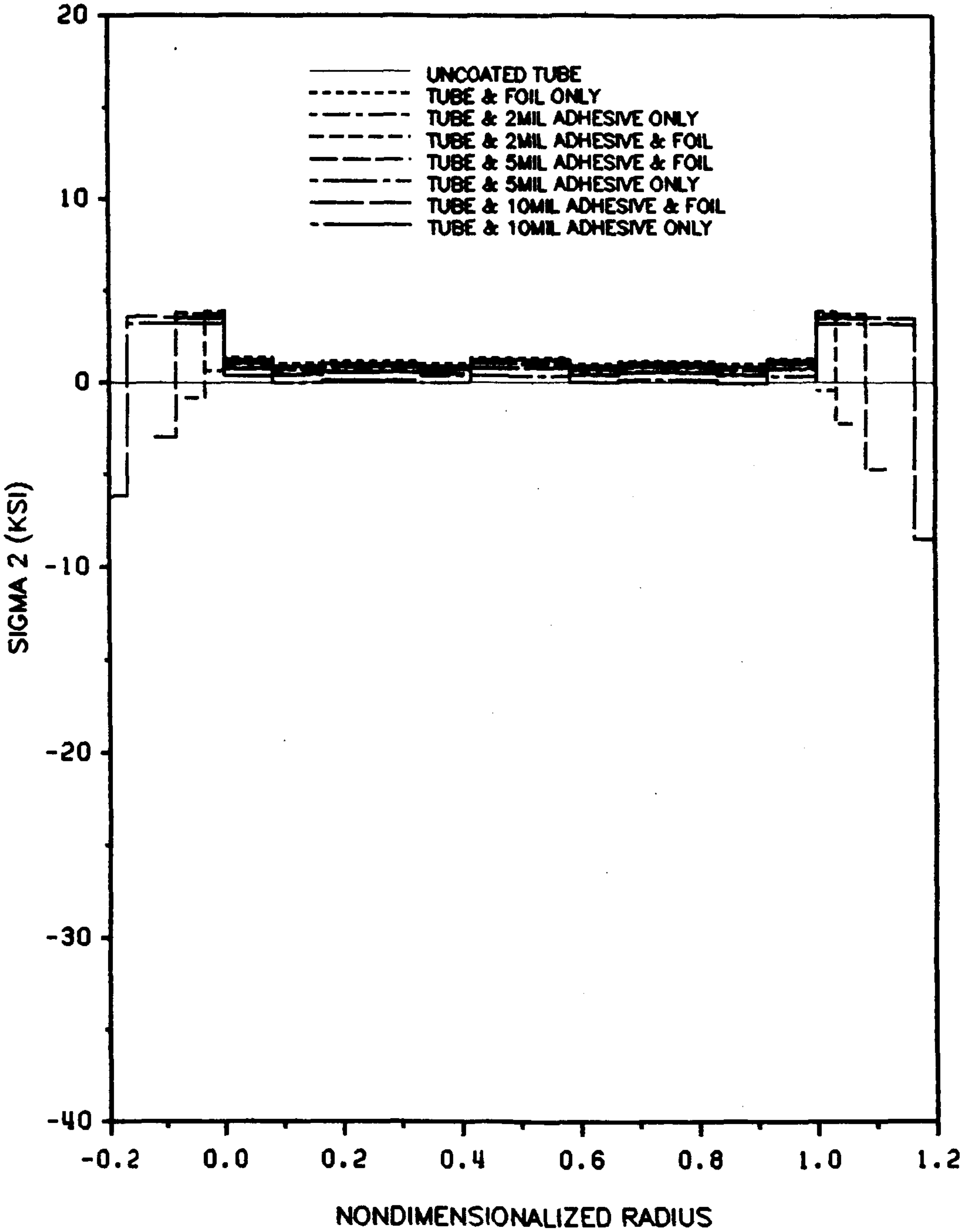

Figure 3b. Transverse and Minor Principal Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

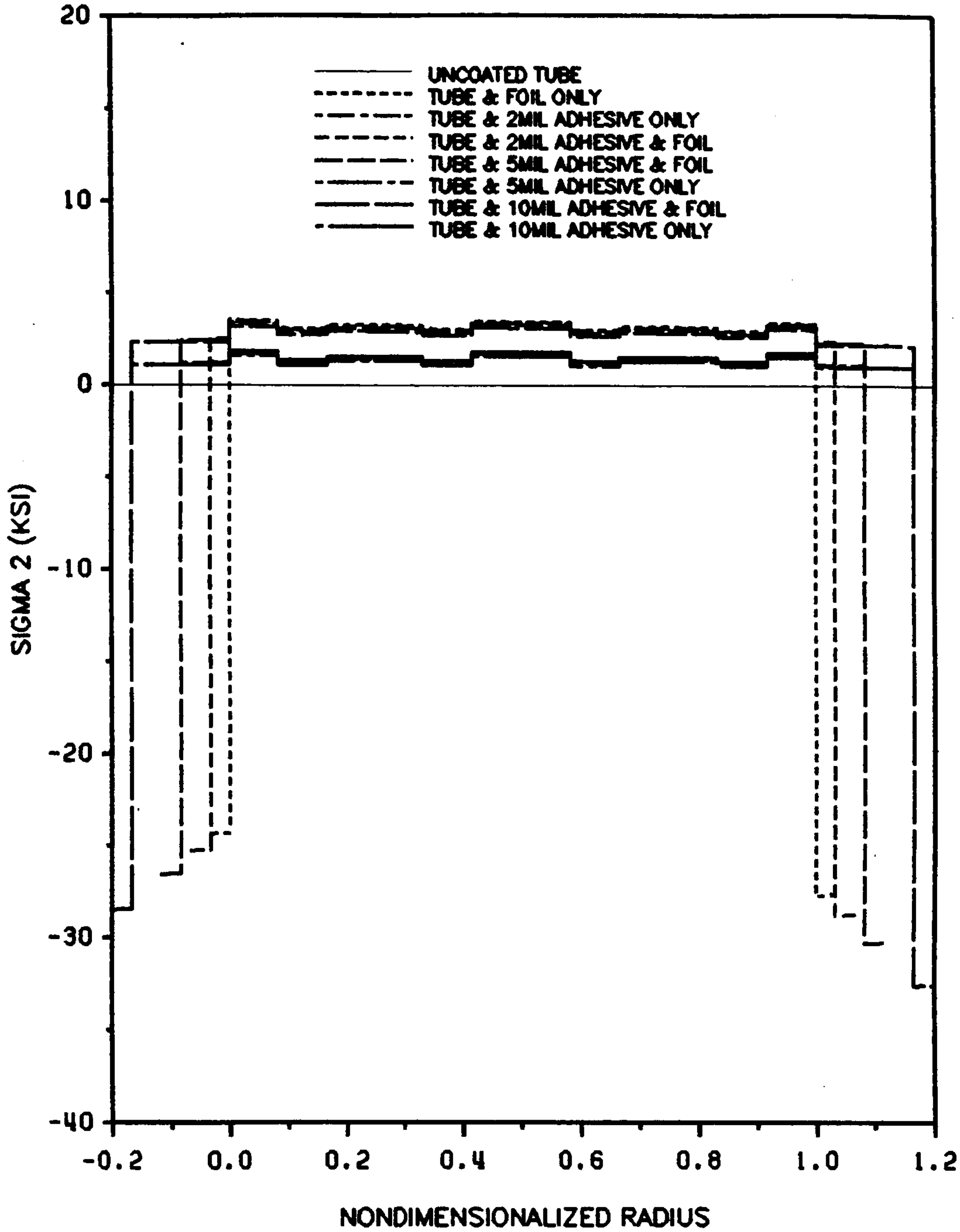

Figure 3c. Transverse and Minor Principal Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

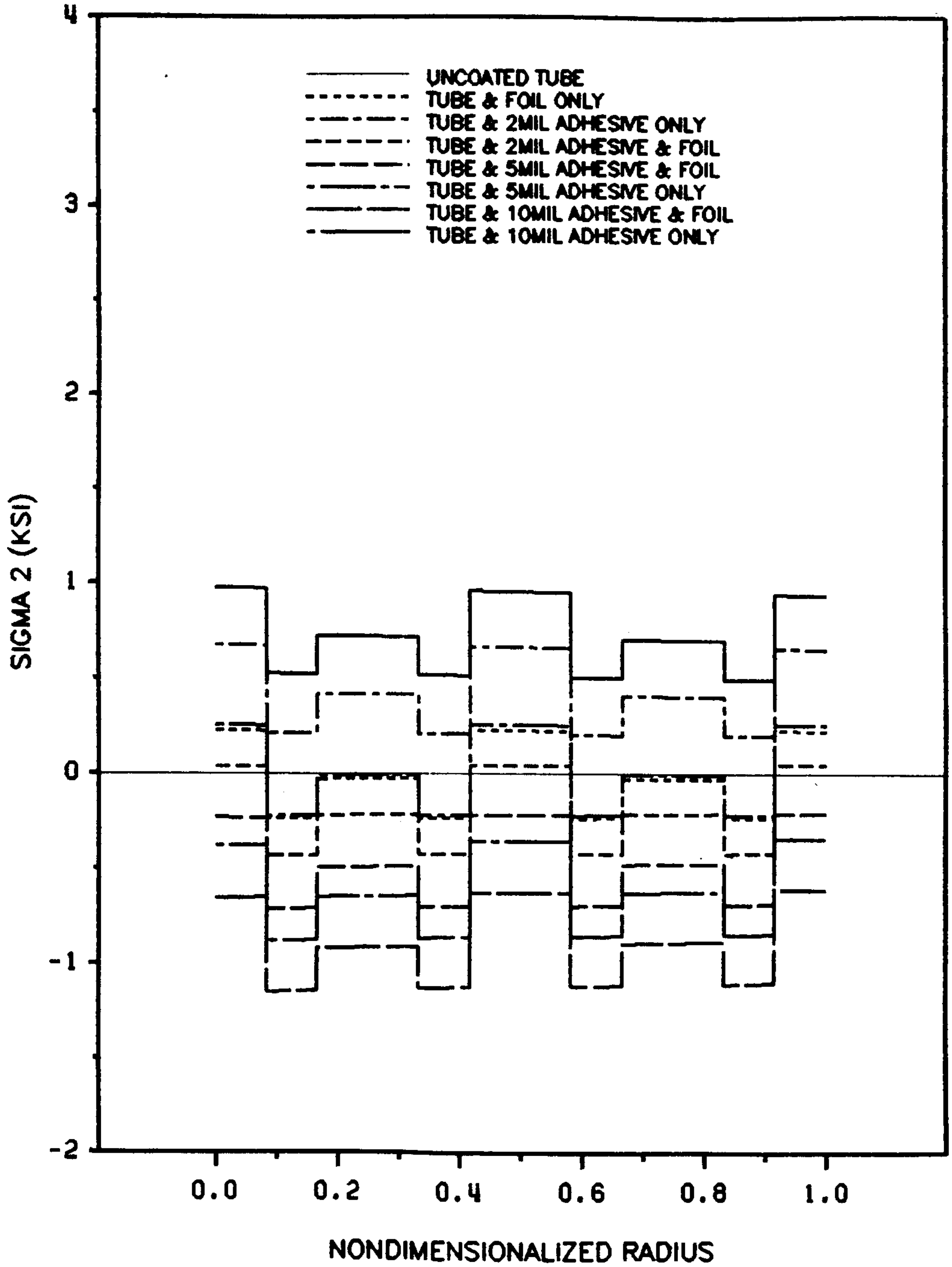

Figure 4a. Details of Transverse Stresses in the T300/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

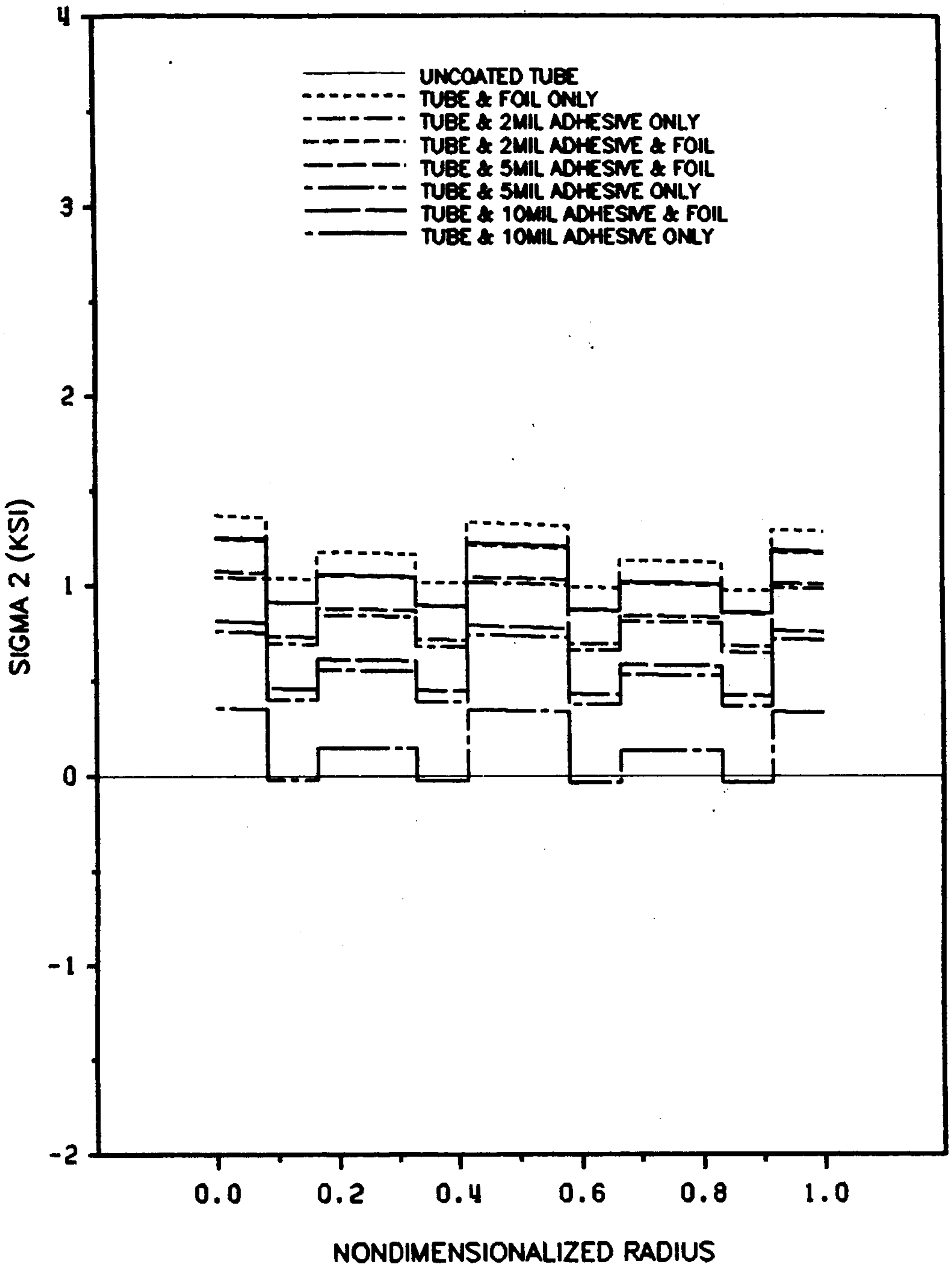

Figure 4b. Details of Transverse Stresses in the P75s/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

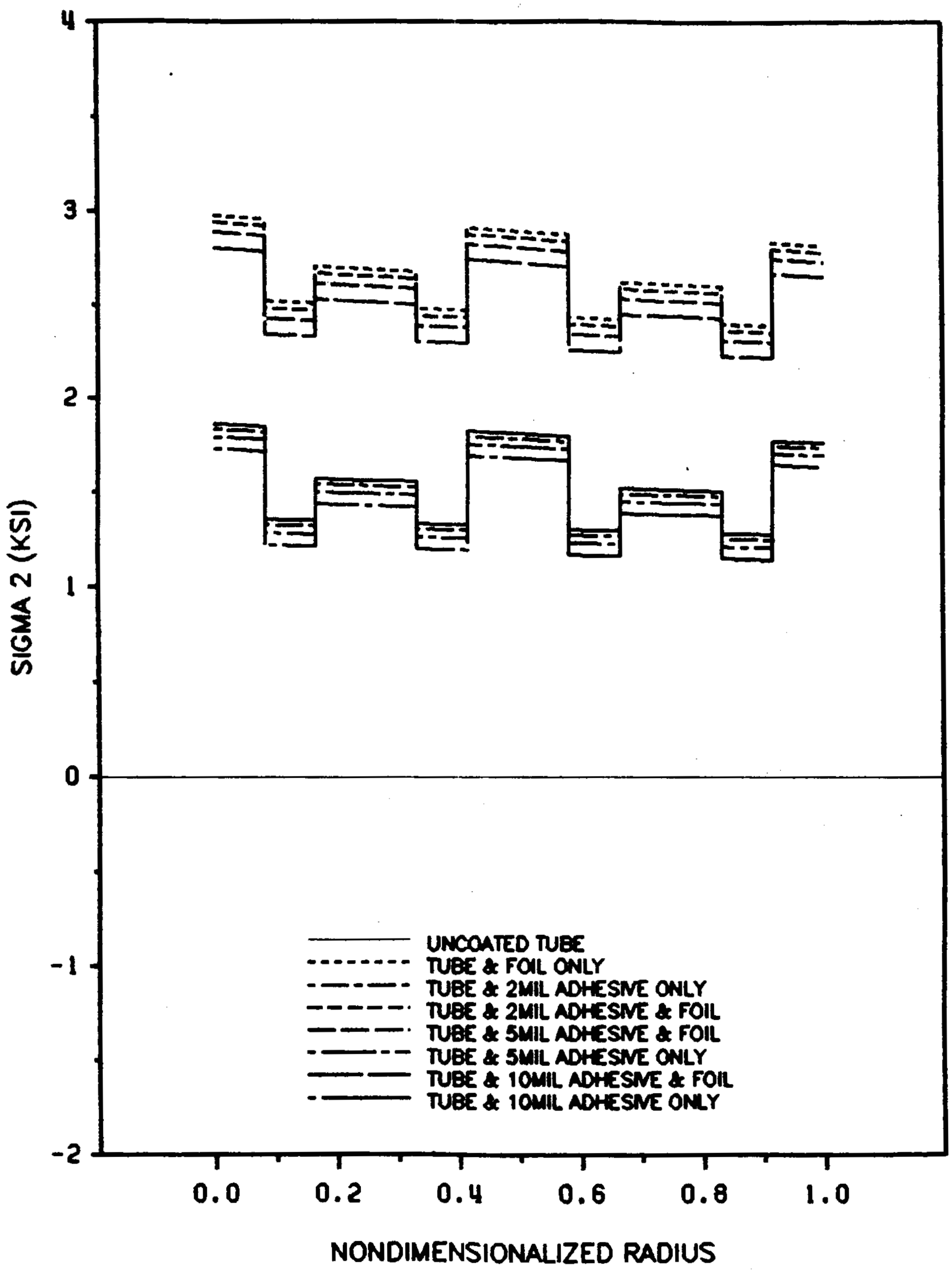

Figure 4c. **Details of Transverse Stresses in the P75s/BP907 Tube at -150° F: Coatings on Inner and Outer Surfaces.**

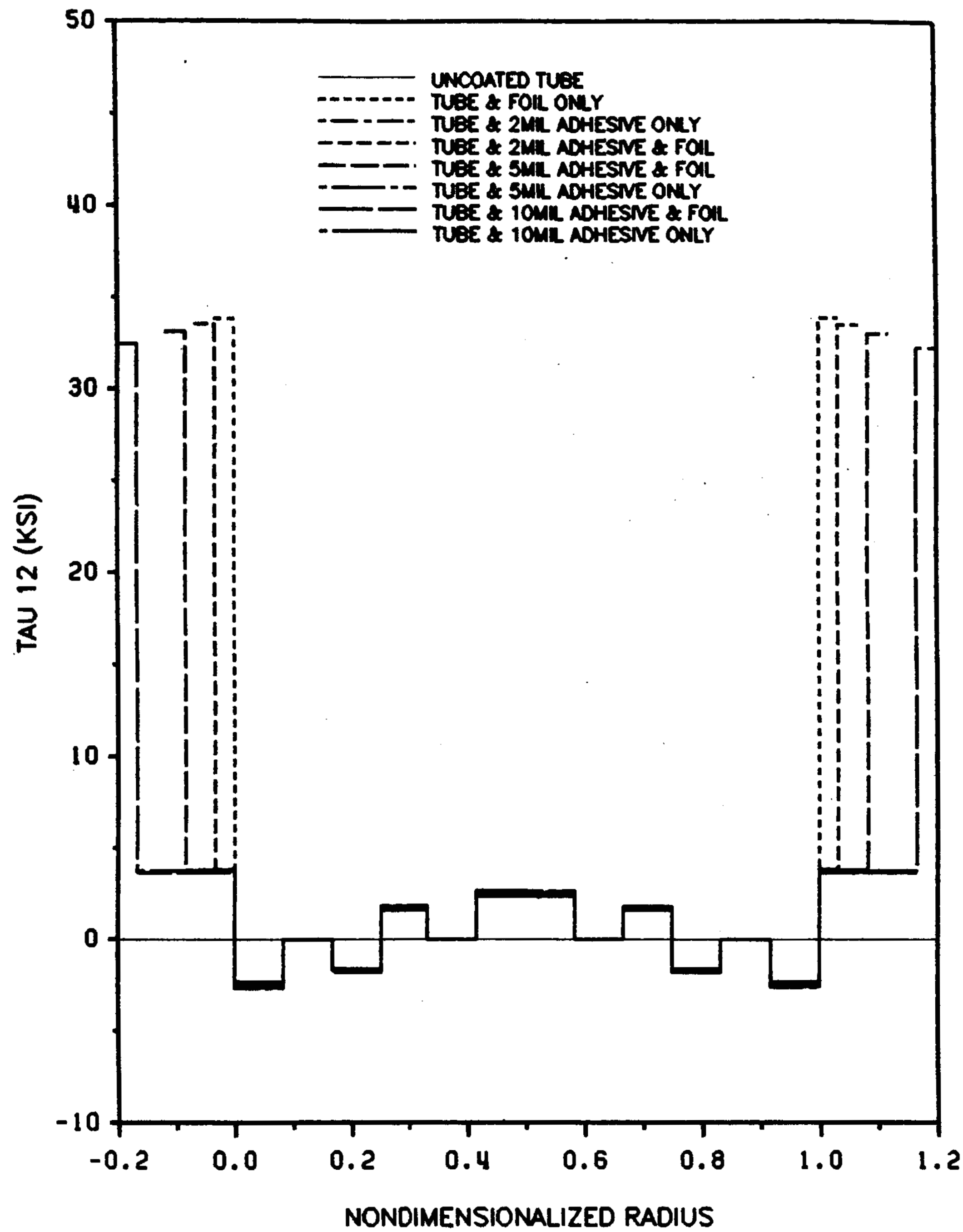

Figure 5a. Shear and Maximum Shear Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

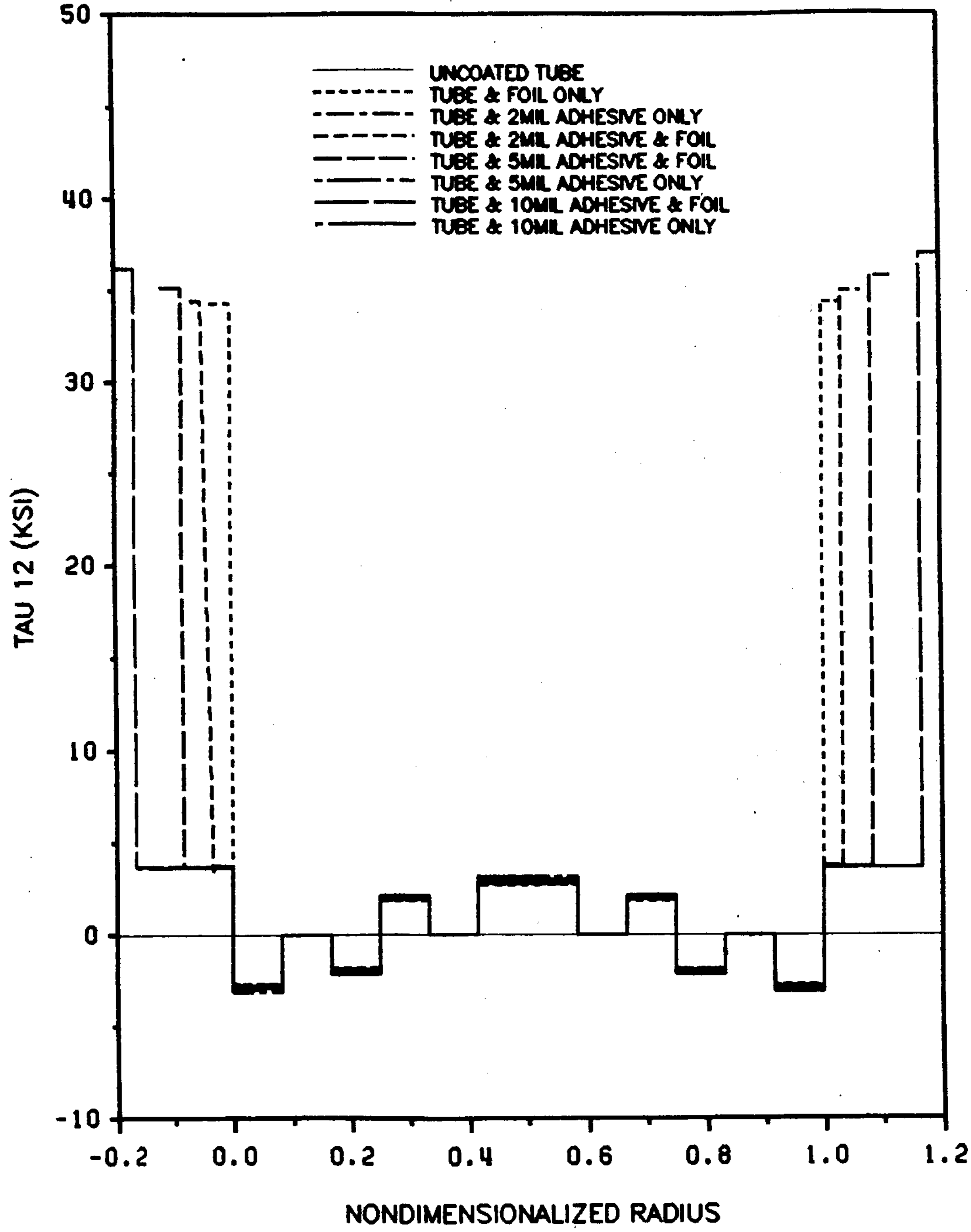

Figure 5b. Shear and Maximum Shear Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

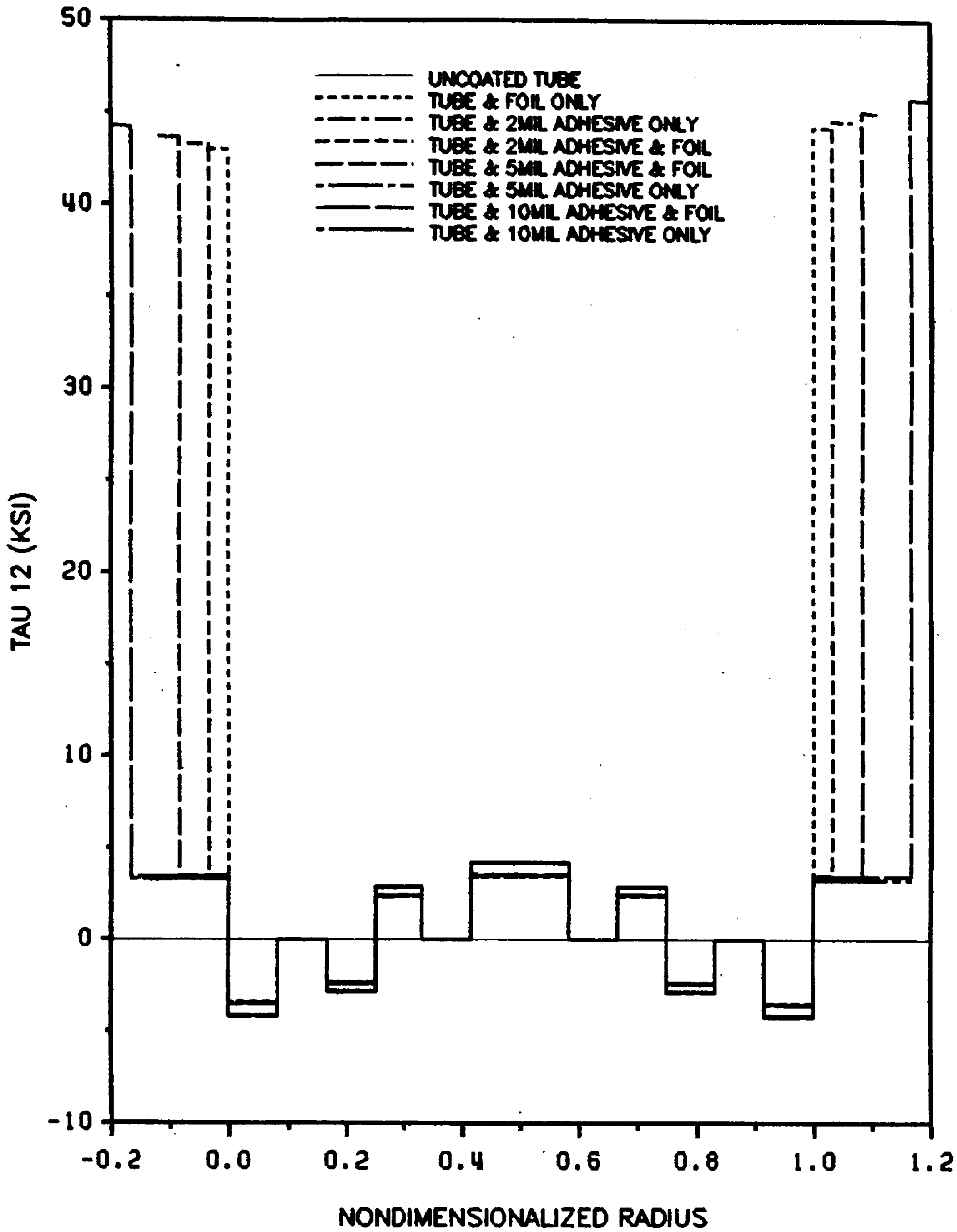

Figure 5c. Shear and Maximum Shear Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

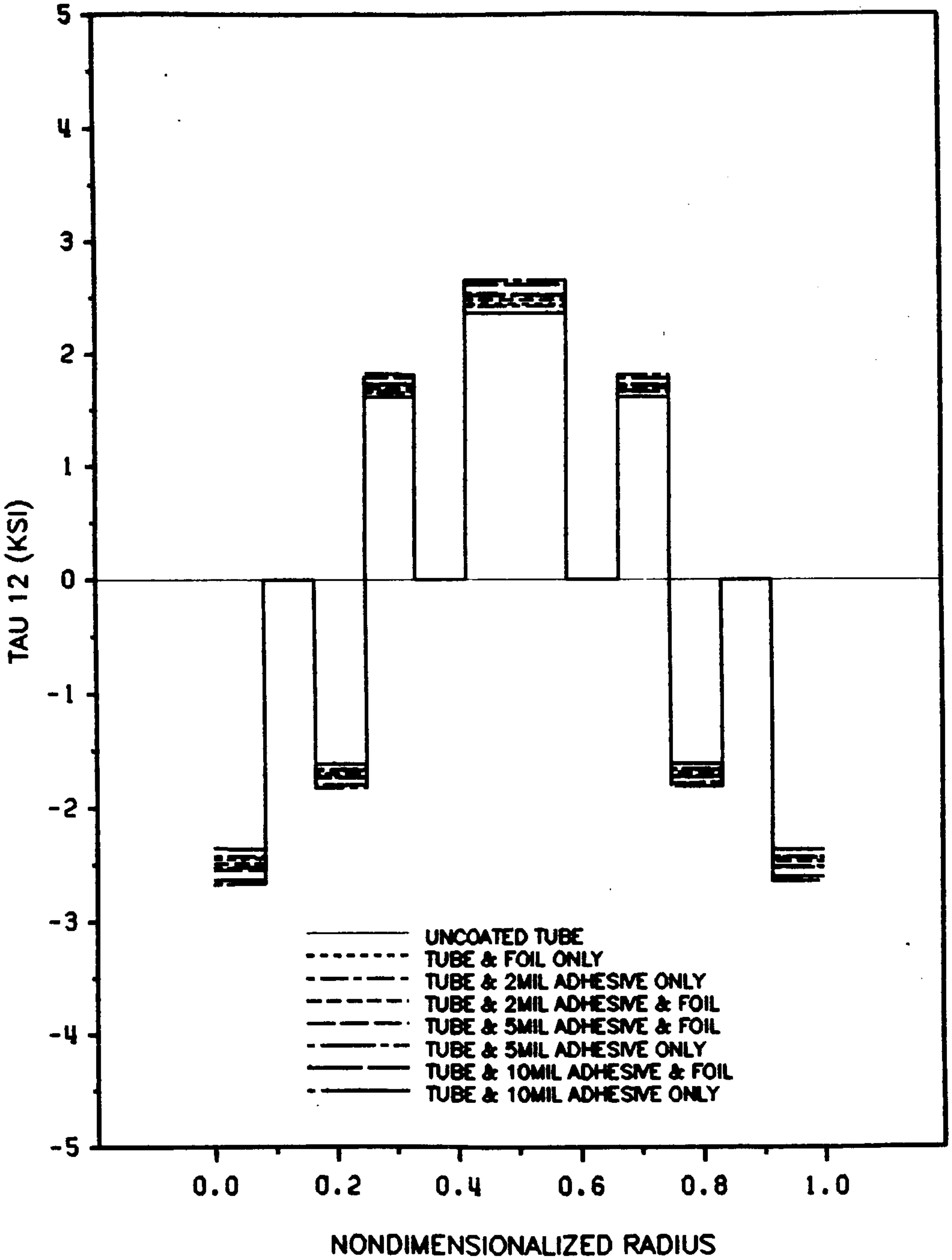

Figure 6a. Details of Shear Stresses in the T300/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

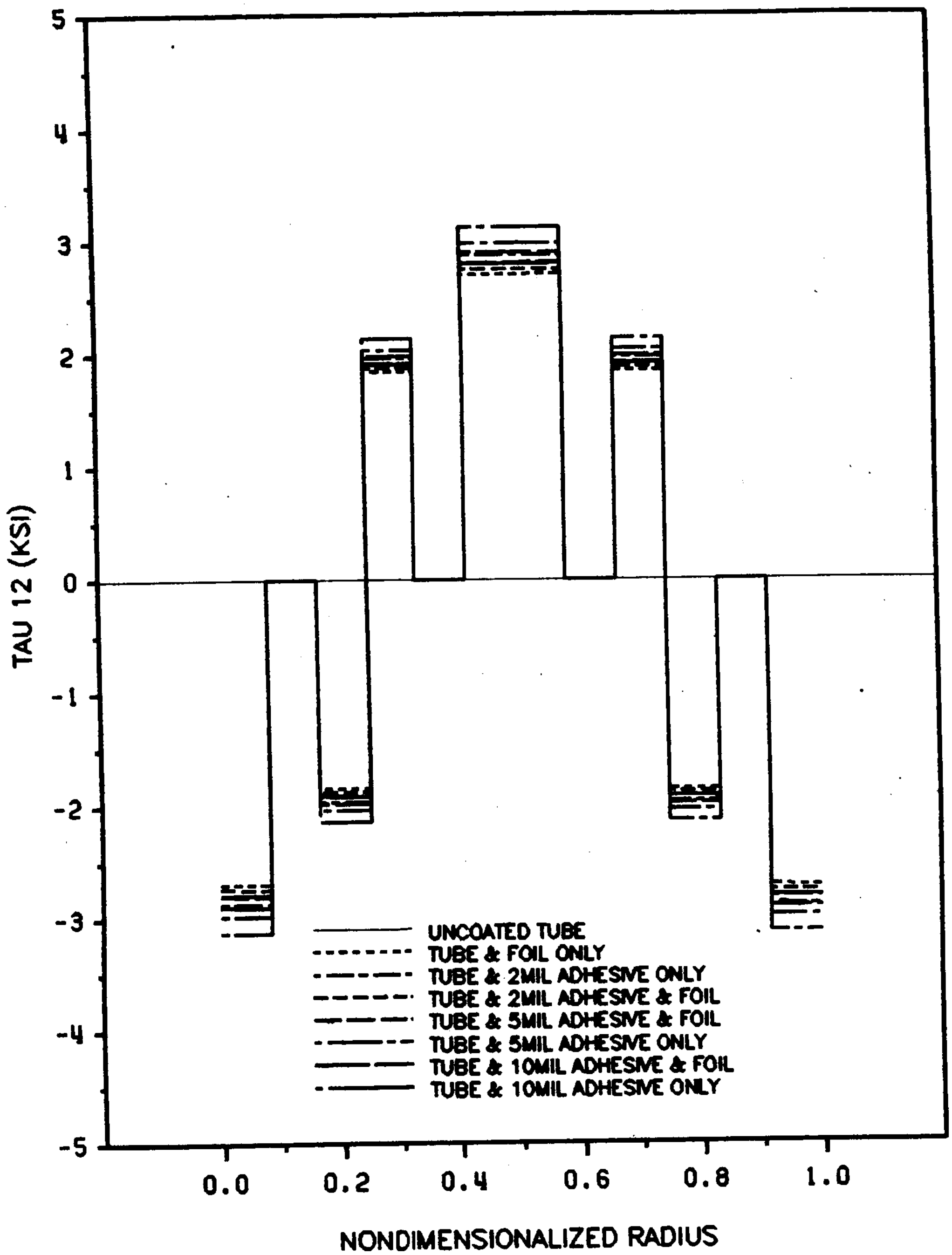

Figure 6b. Details of Shear Stresses in the P75s/934 Tube at -150° F: Coatings on Inner and Outer Surfaces.

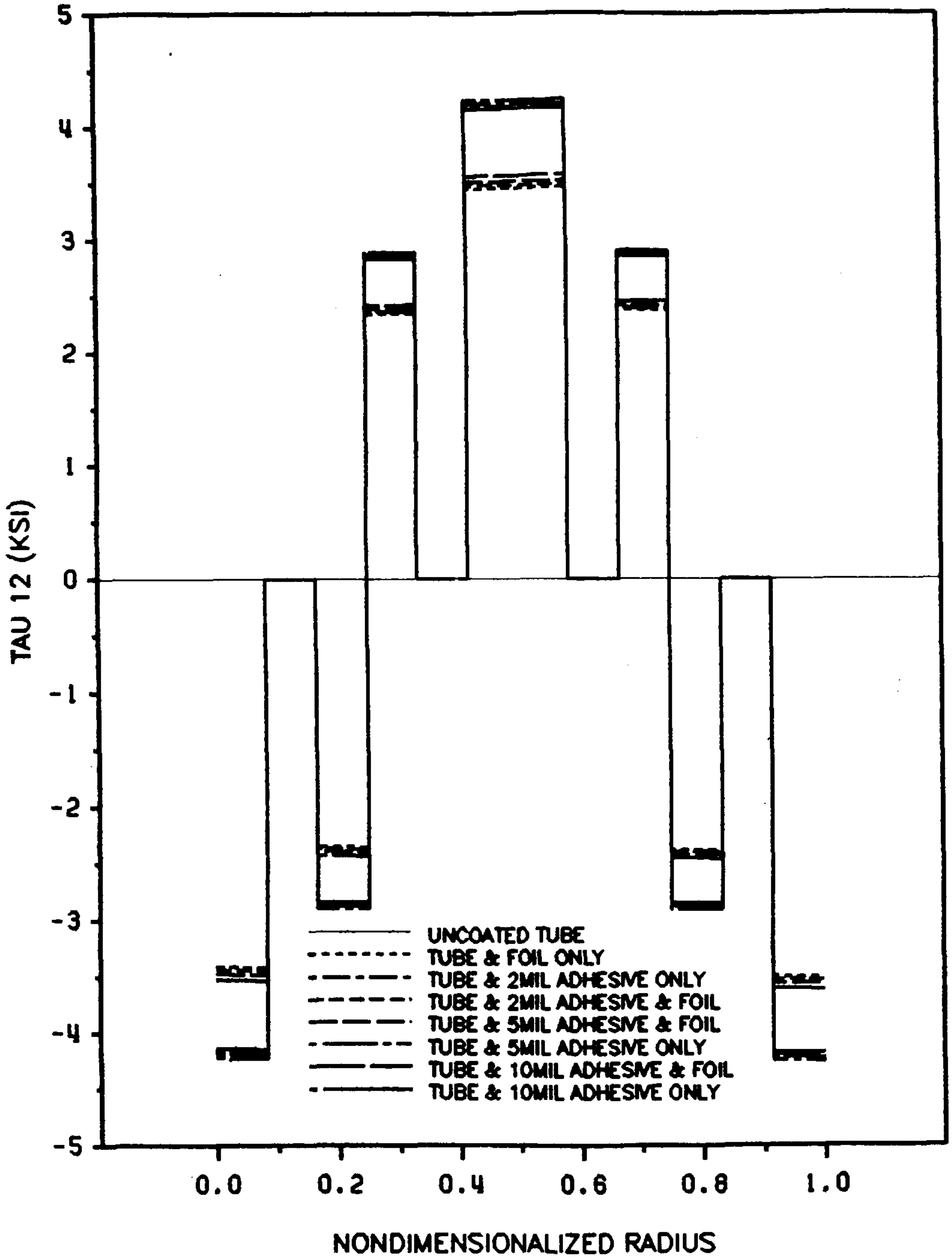

Figure 6c. Details of Shear Stresses in the P75s/BP907 Tube at -150° F: Coatings on Inner and Outer Surfaces.

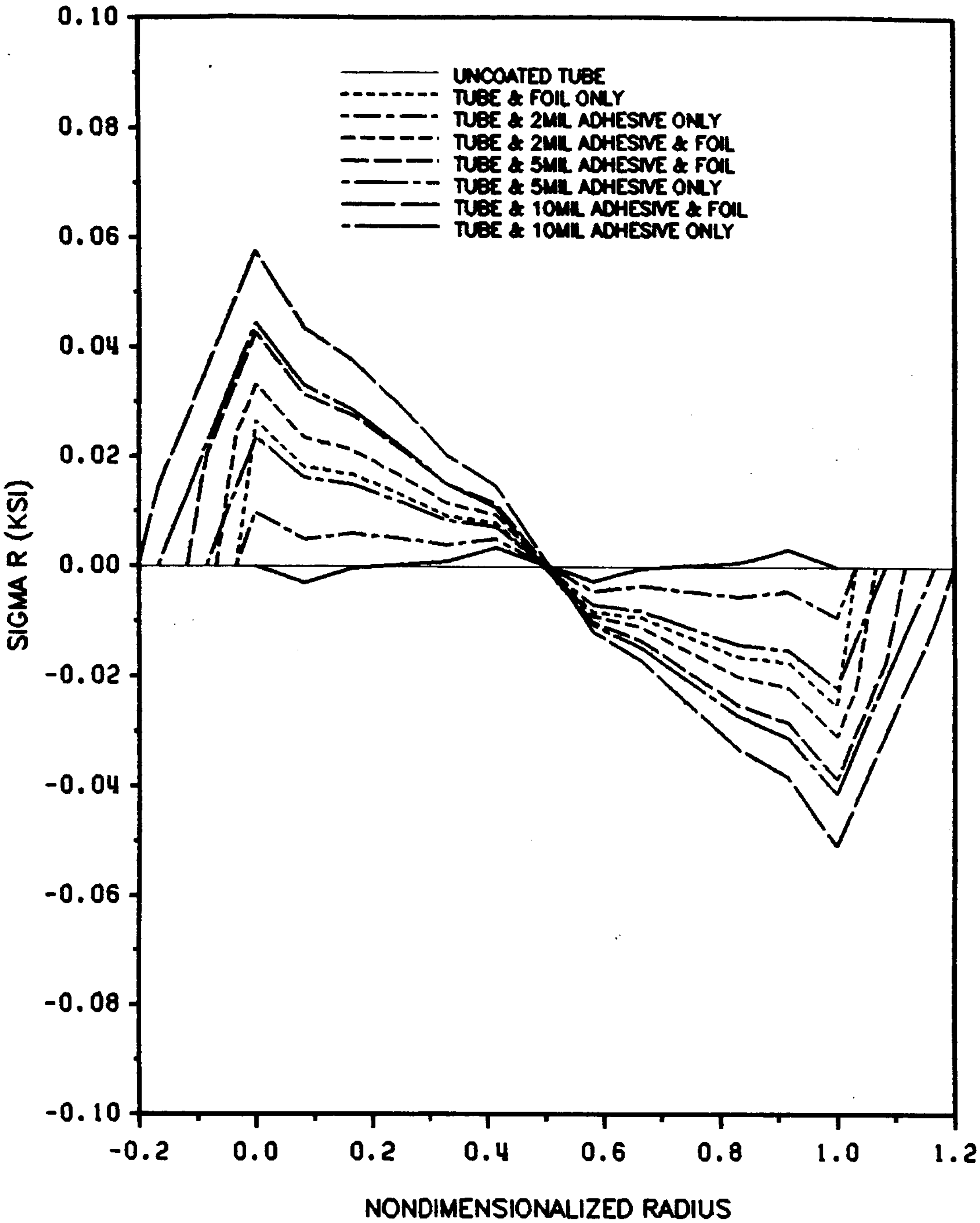

Figure 7a. Radial Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

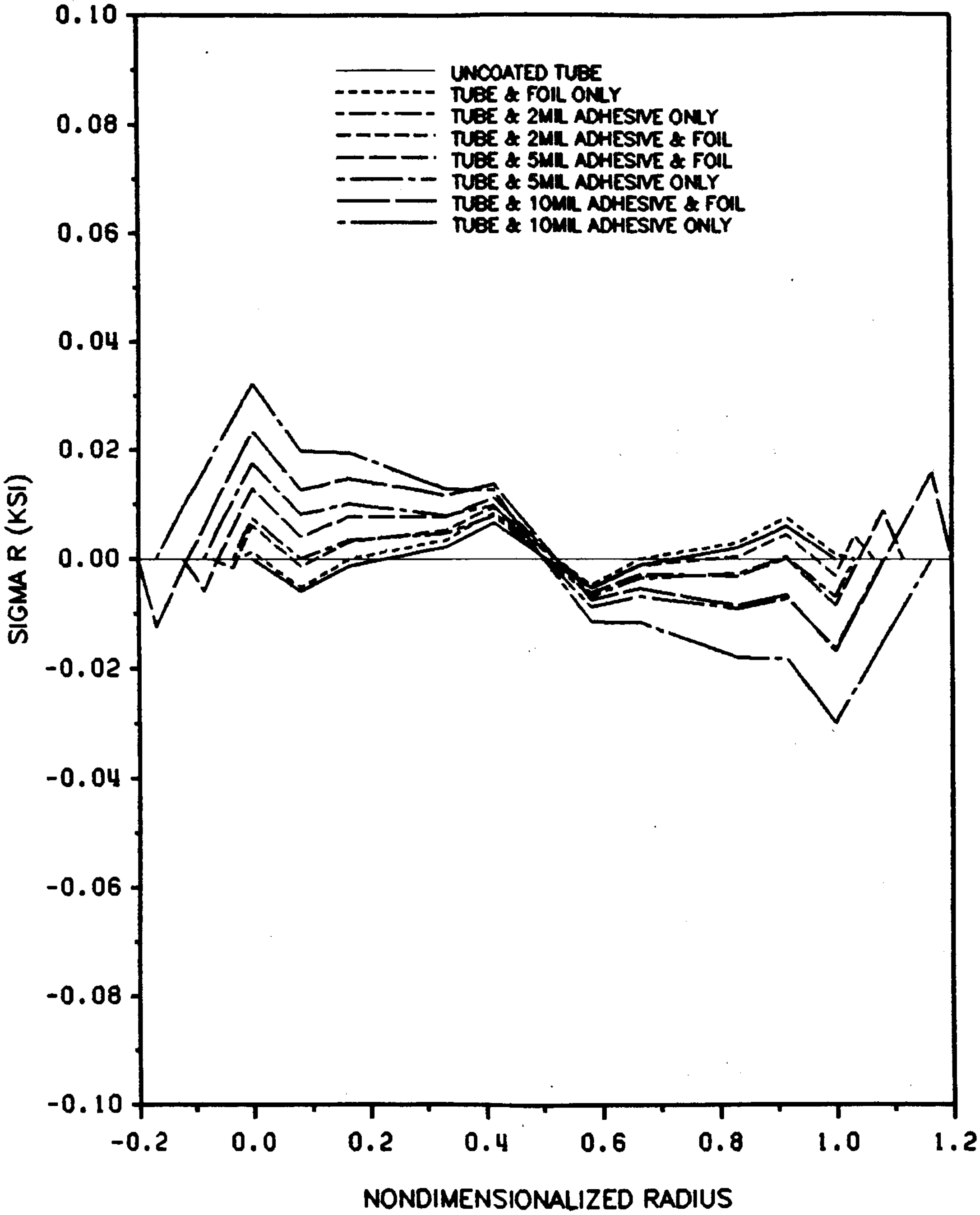

Figure 7b. Radial Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

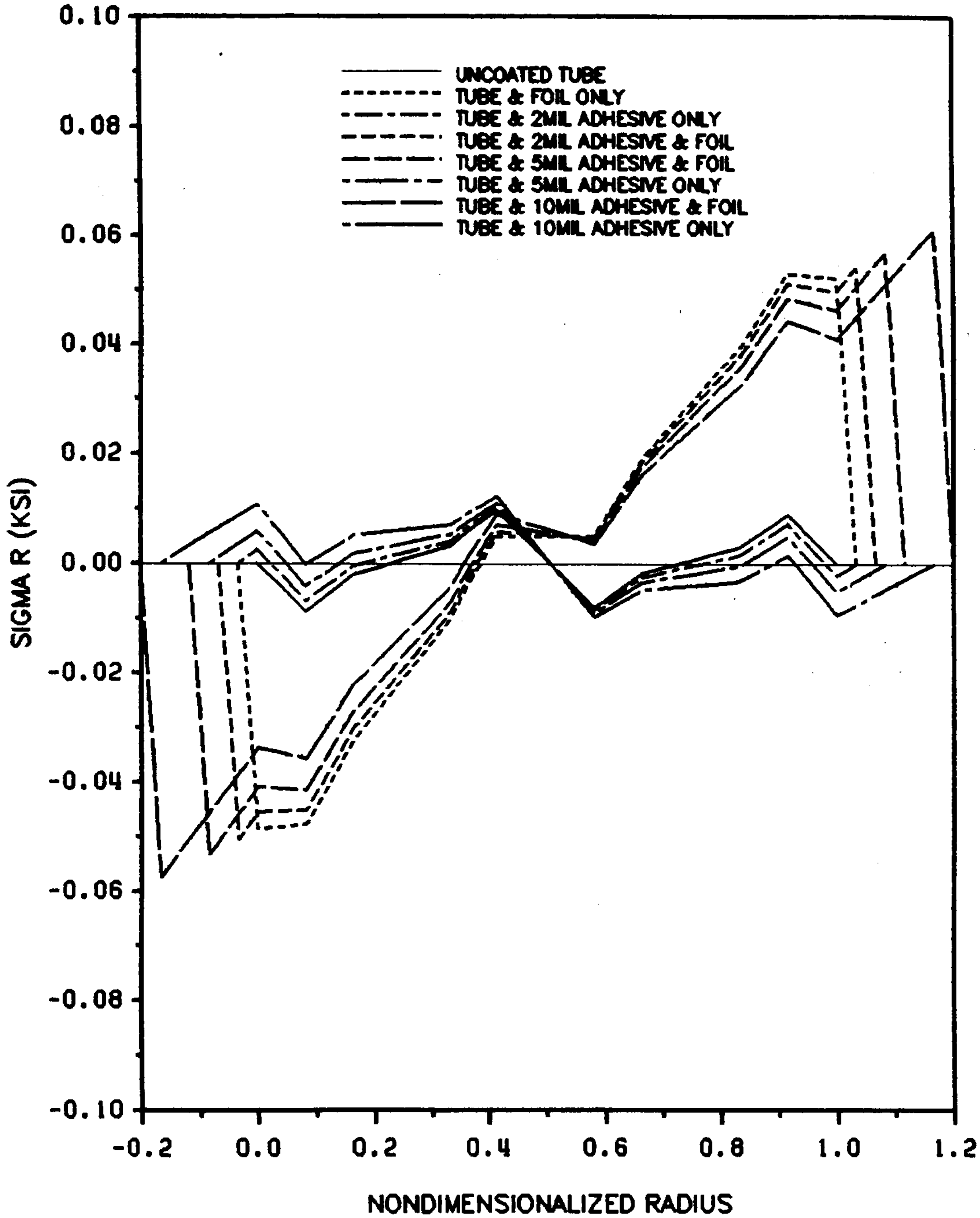

Figure 7c. Radial Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Inner and Outer Surfaces.

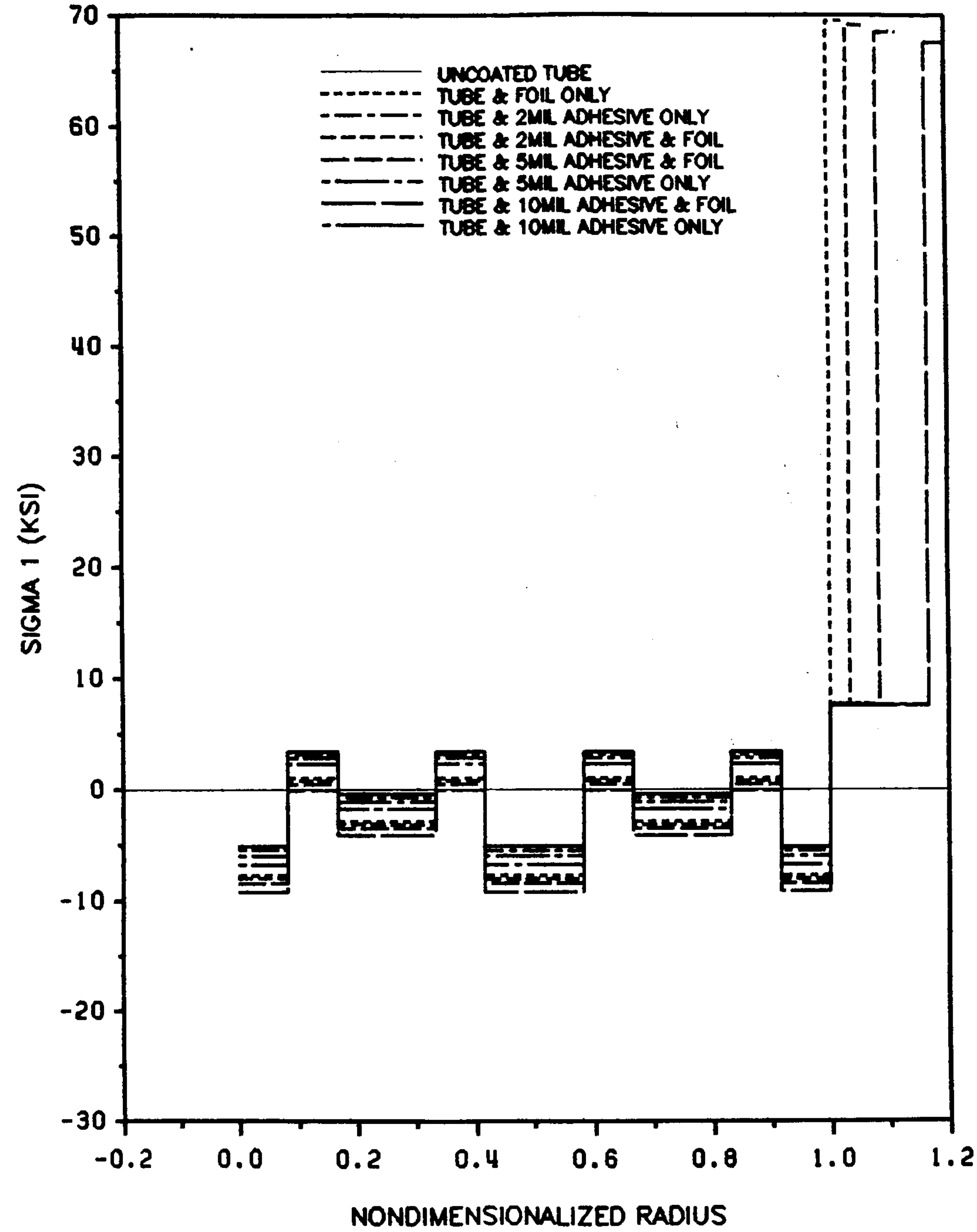

Figure 8a. Fiber Direction and Major Principal Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

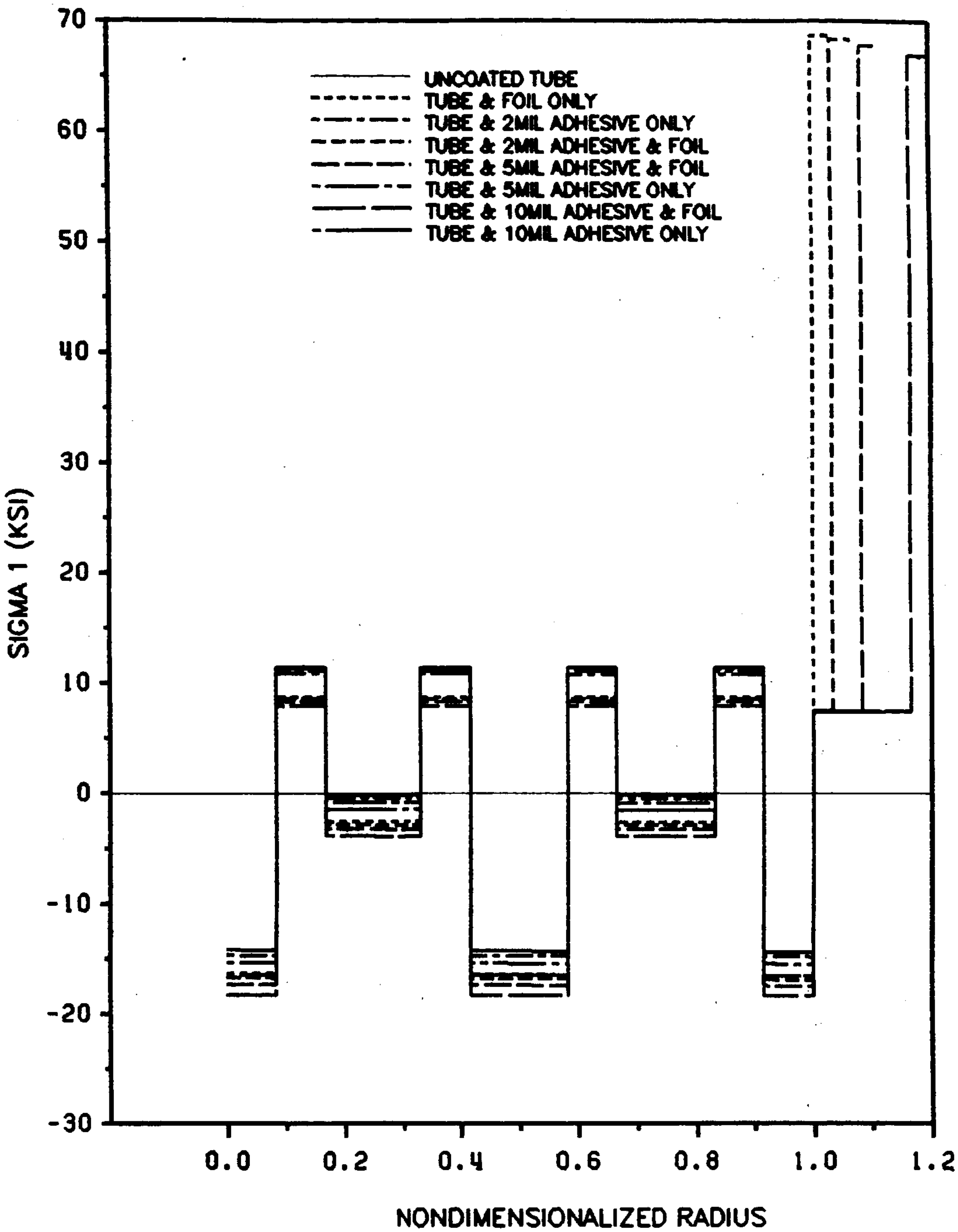

Figure 8b. Fiber Direction and Major Principal Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

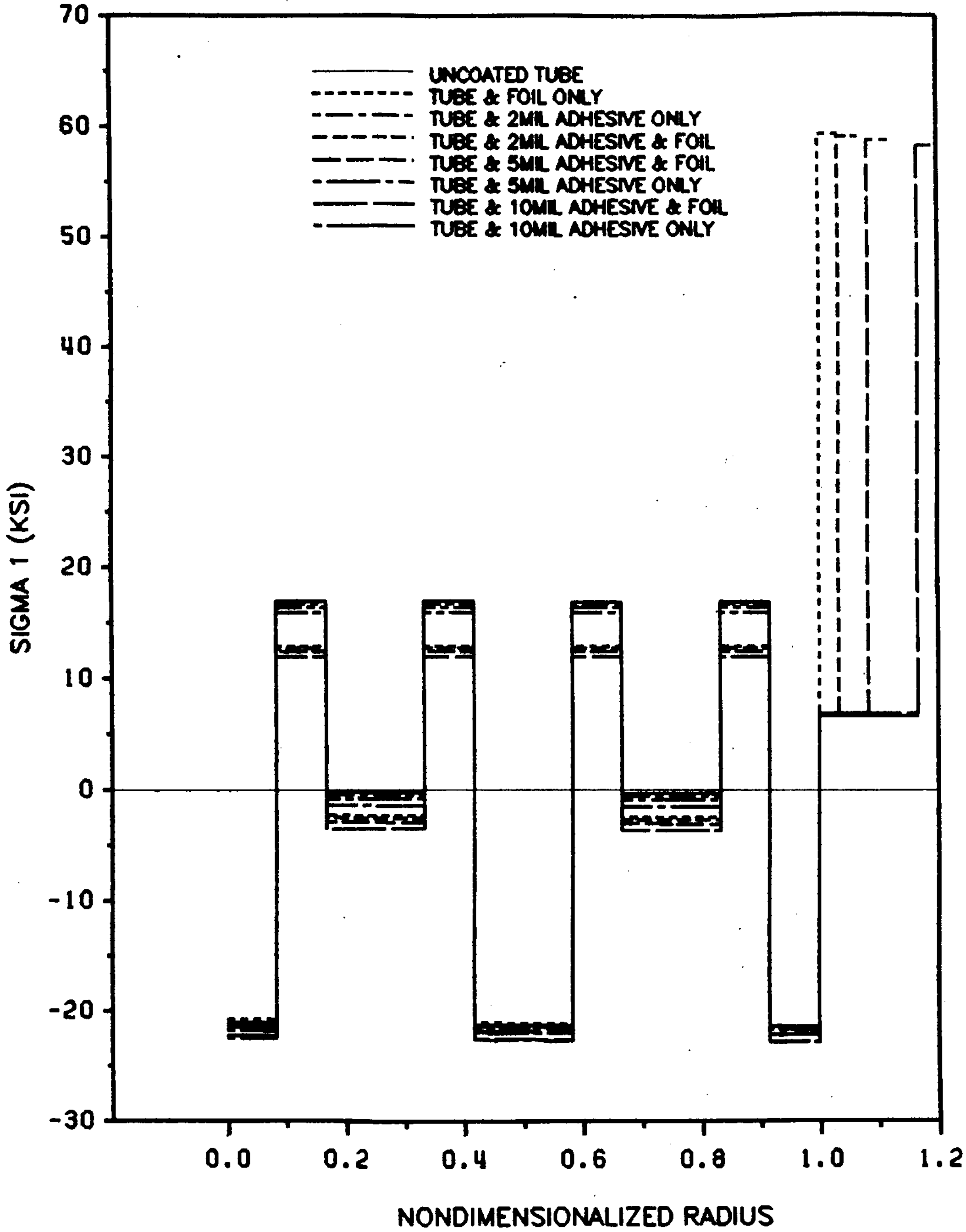

Figure 8c. Fiber Direction and Major Principal Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

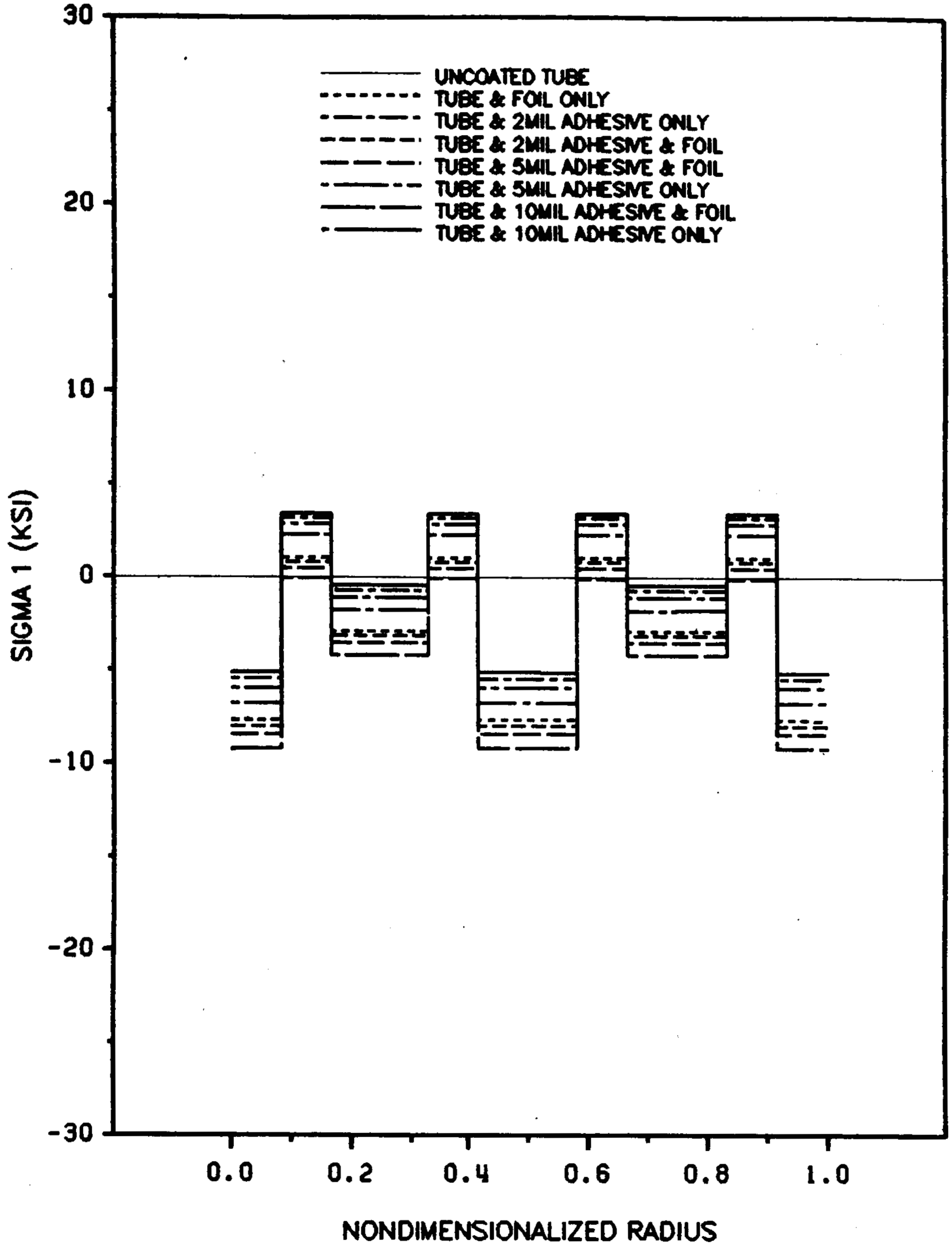

Figure 9a. Details of Fiber Direction Stresses in the T300/934 Tube at -150° F: Coatings on Outer Surface Only.

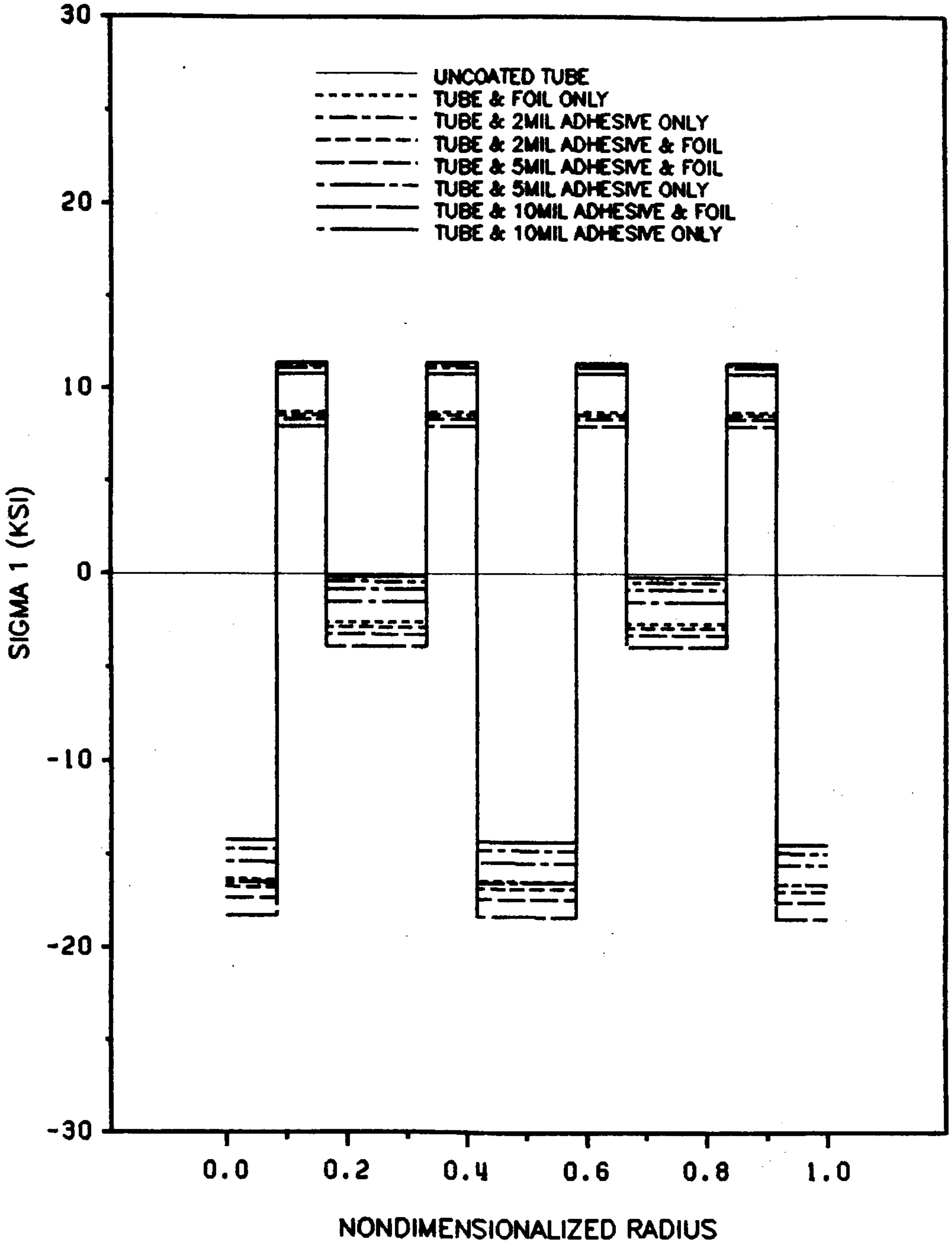

Figure 9b. Details of Fiber Direction Stresses in the P75s/934 Tube at -150° F: Coatings on Outer Surface Only.

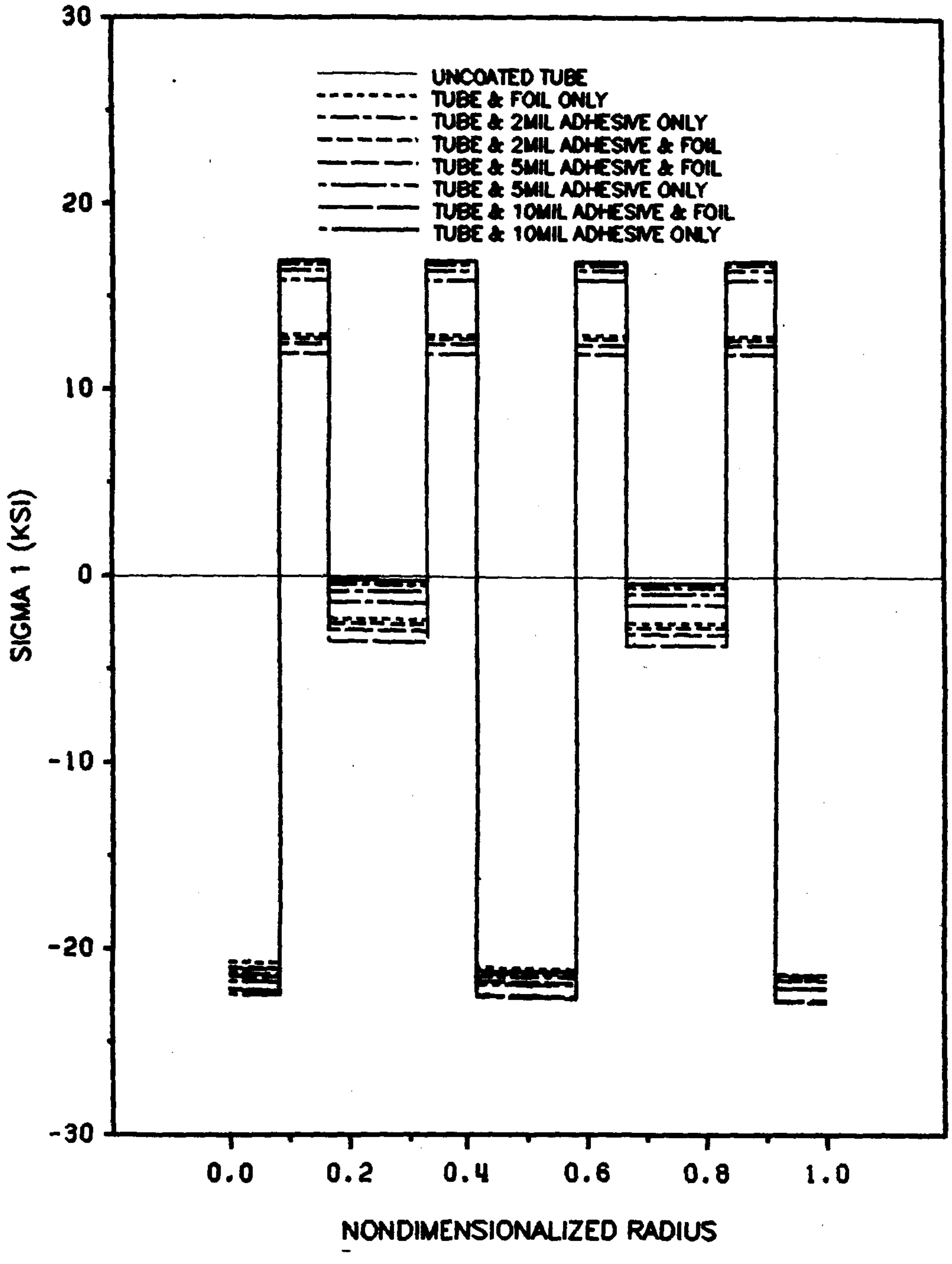

Figure 9c. Details of Fiber Direction Stresses in the P75s/BP907 Tube at -150° F: Coatings on Outer Surface Only.

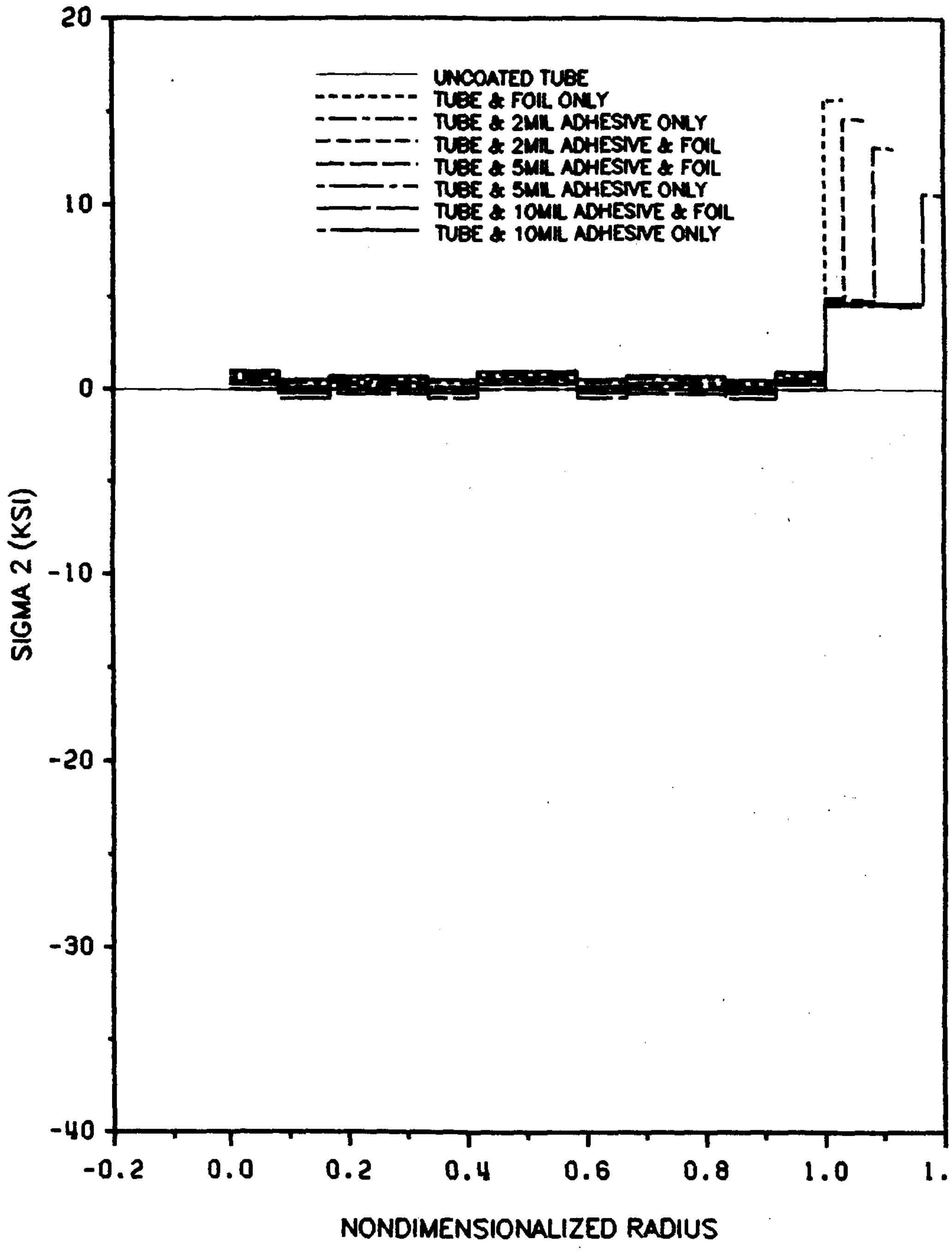

Figure 10a. **Transverse and Minor Principal Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.**

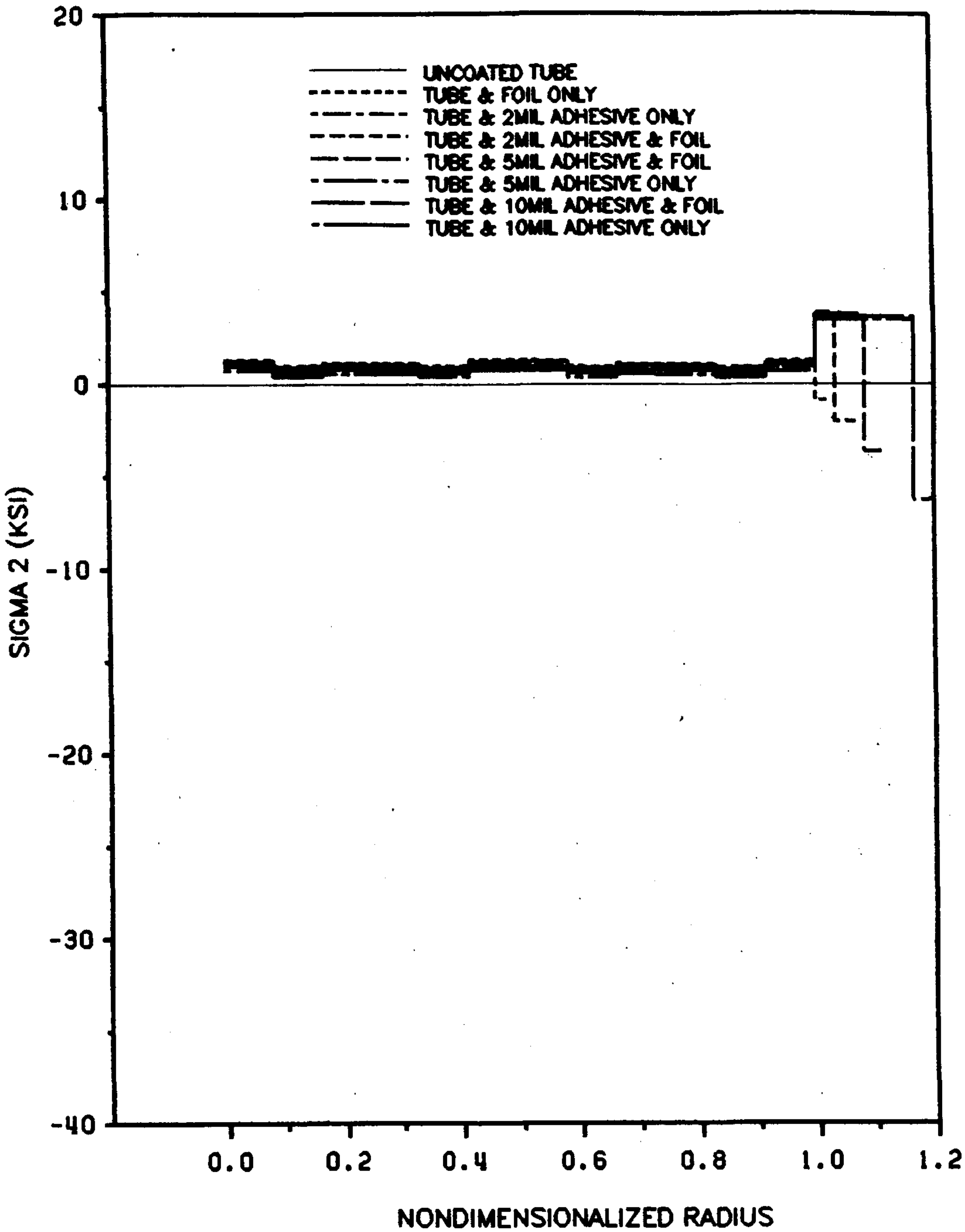

Figure 10b. Transverse and Minor Principal Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

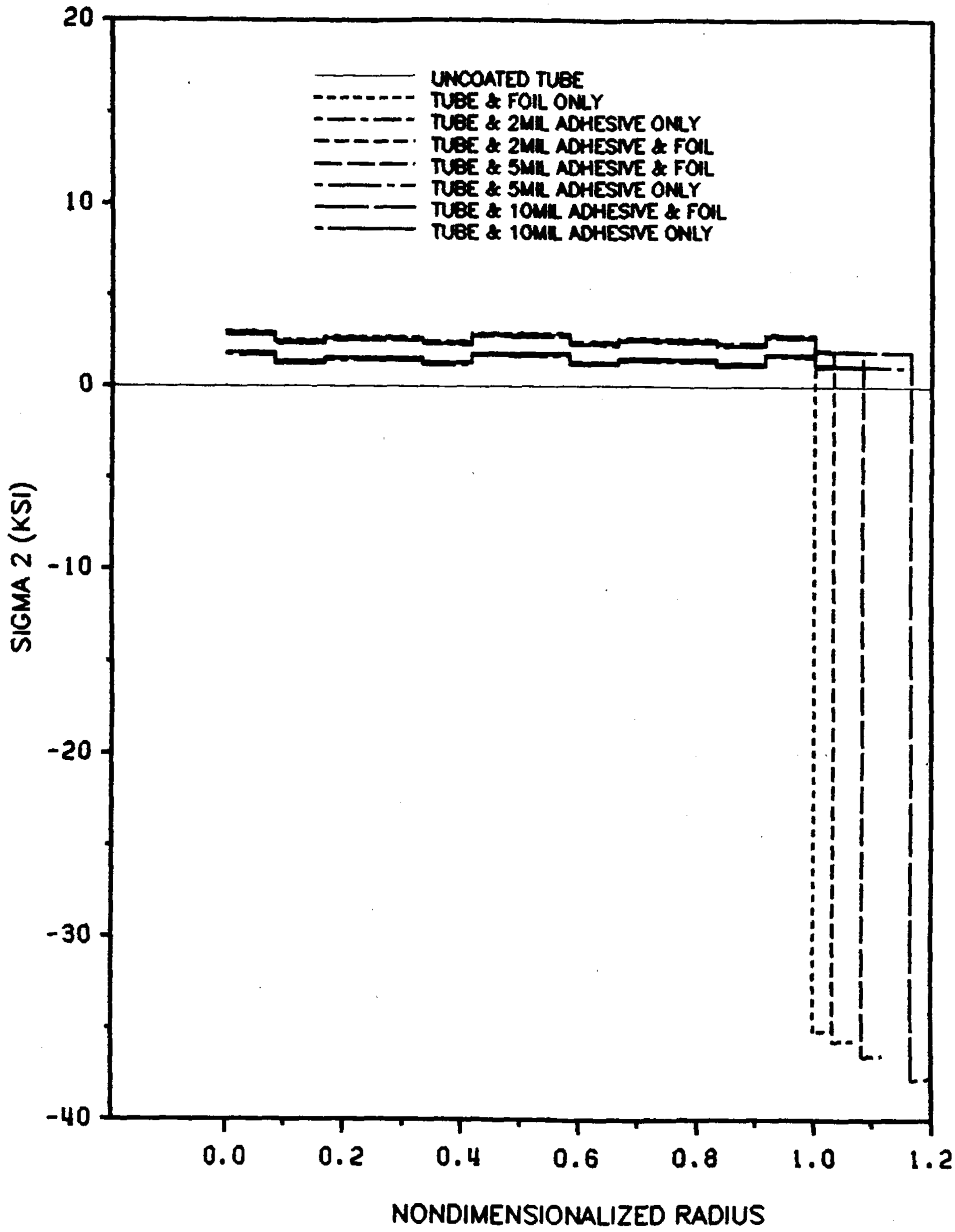

Figure 10c. **Transverse and Minor Principal Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.**

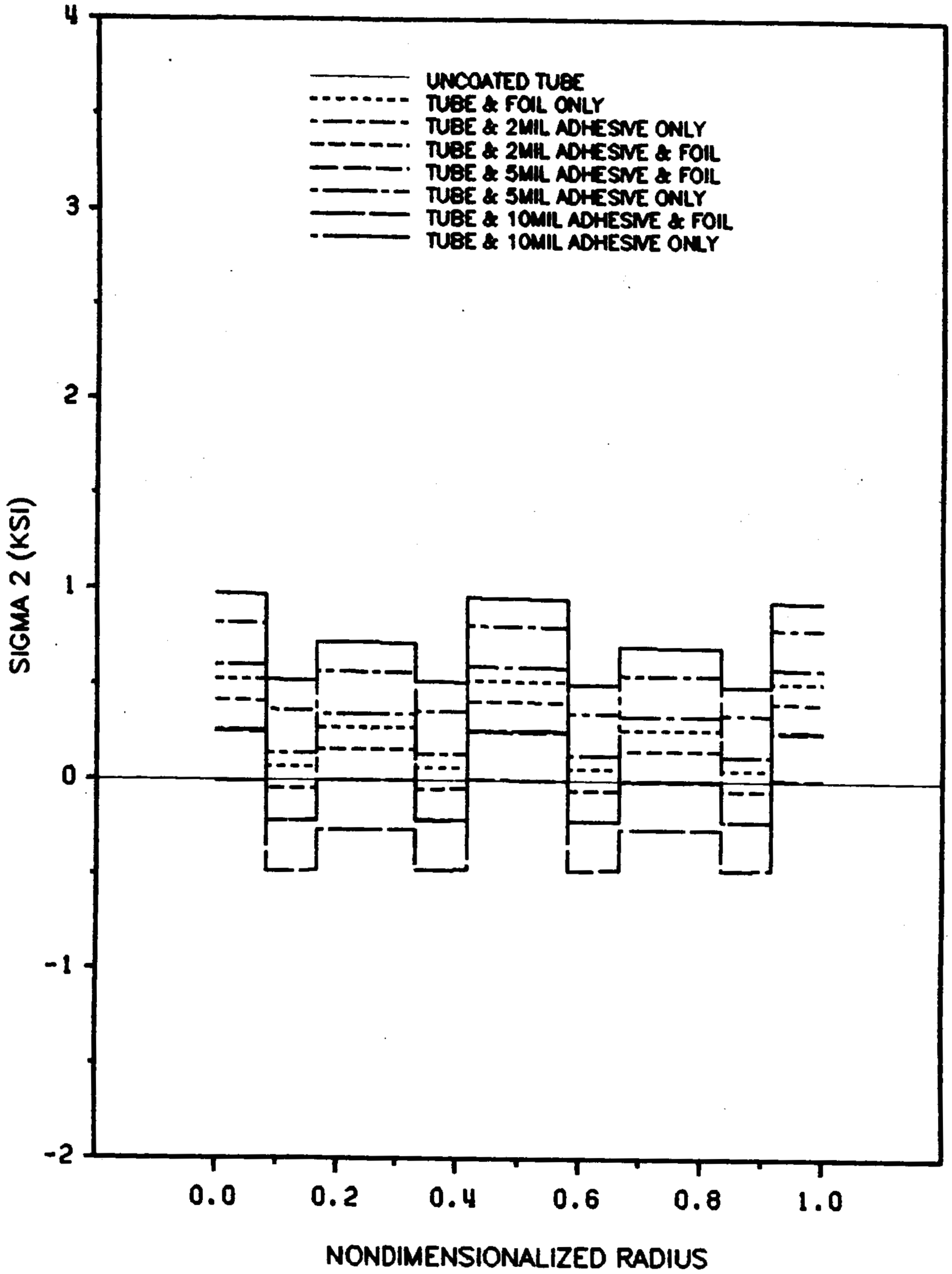

Figure 11a. Details of Transverse Stresses in the T300/934 Tube at -150° F: Coatings on Outer Surface Only.

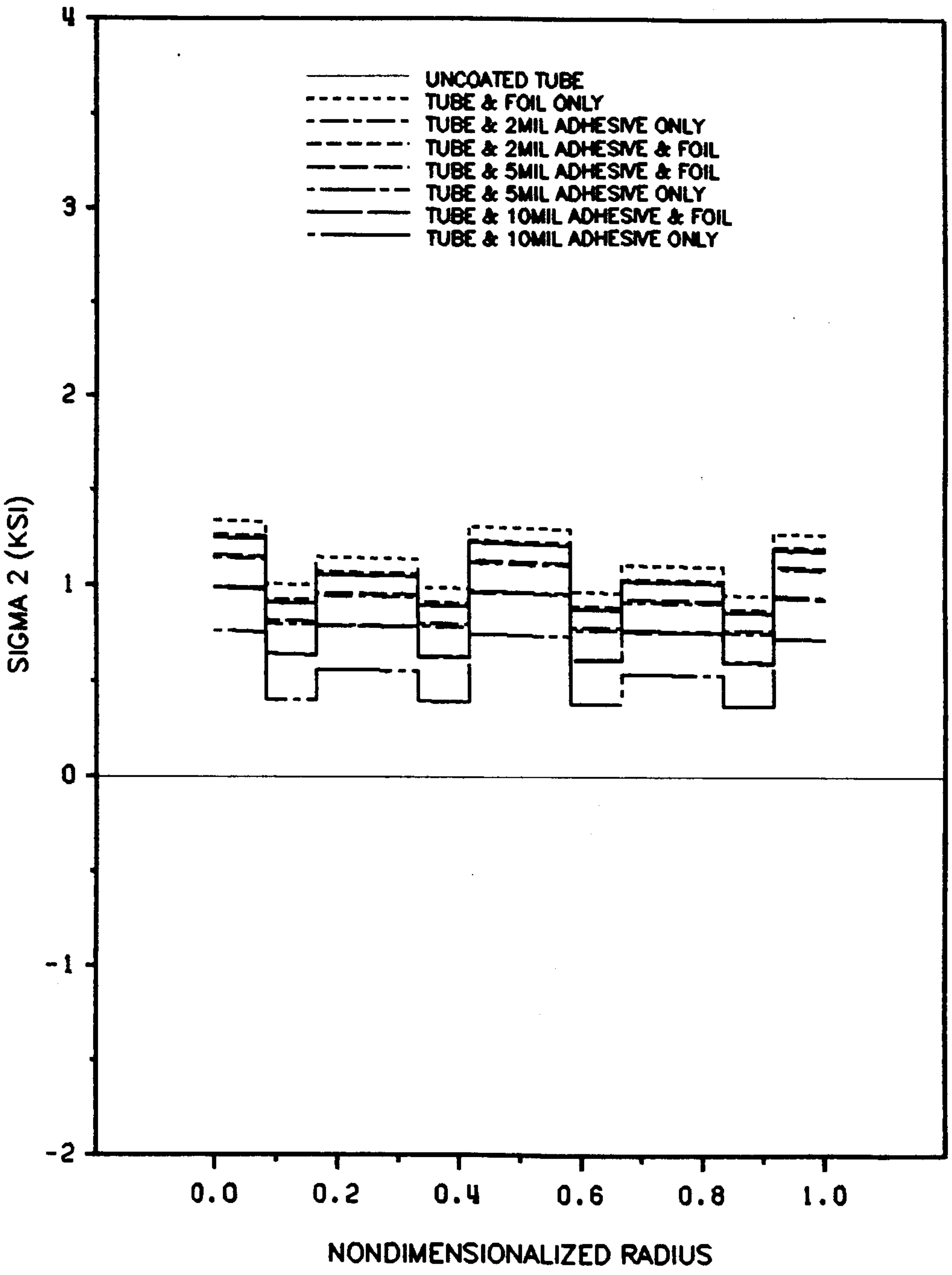

Figure 11b. Details of Transverse Stresses in the P75s/934 Tube at -150° F: Coatings on Outer Surface Only.

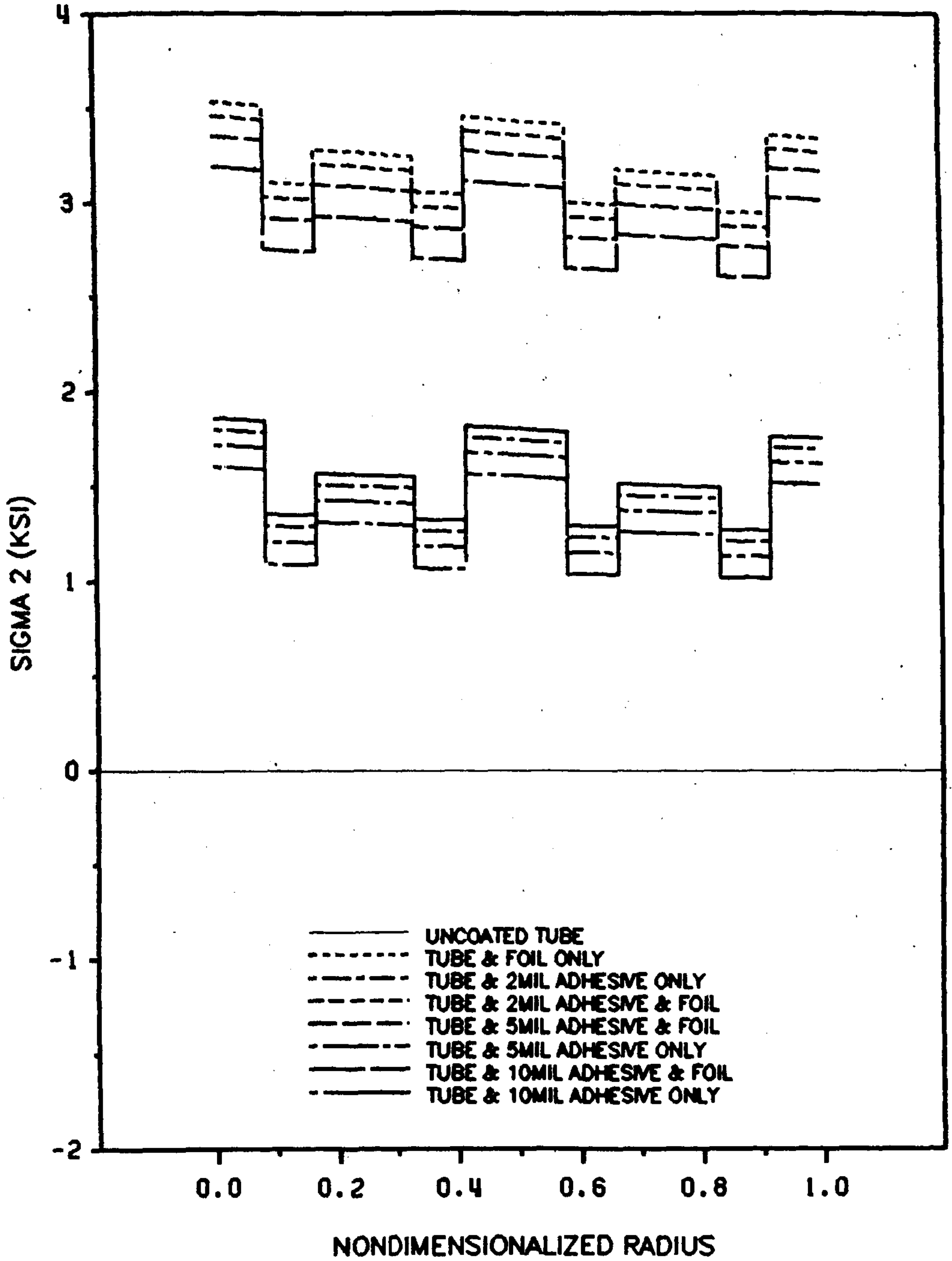

Figure 11c. Details of Transverse Stresses in the P75s/BP907 Tube at -150° F: Coatings on Outer Surface Only.

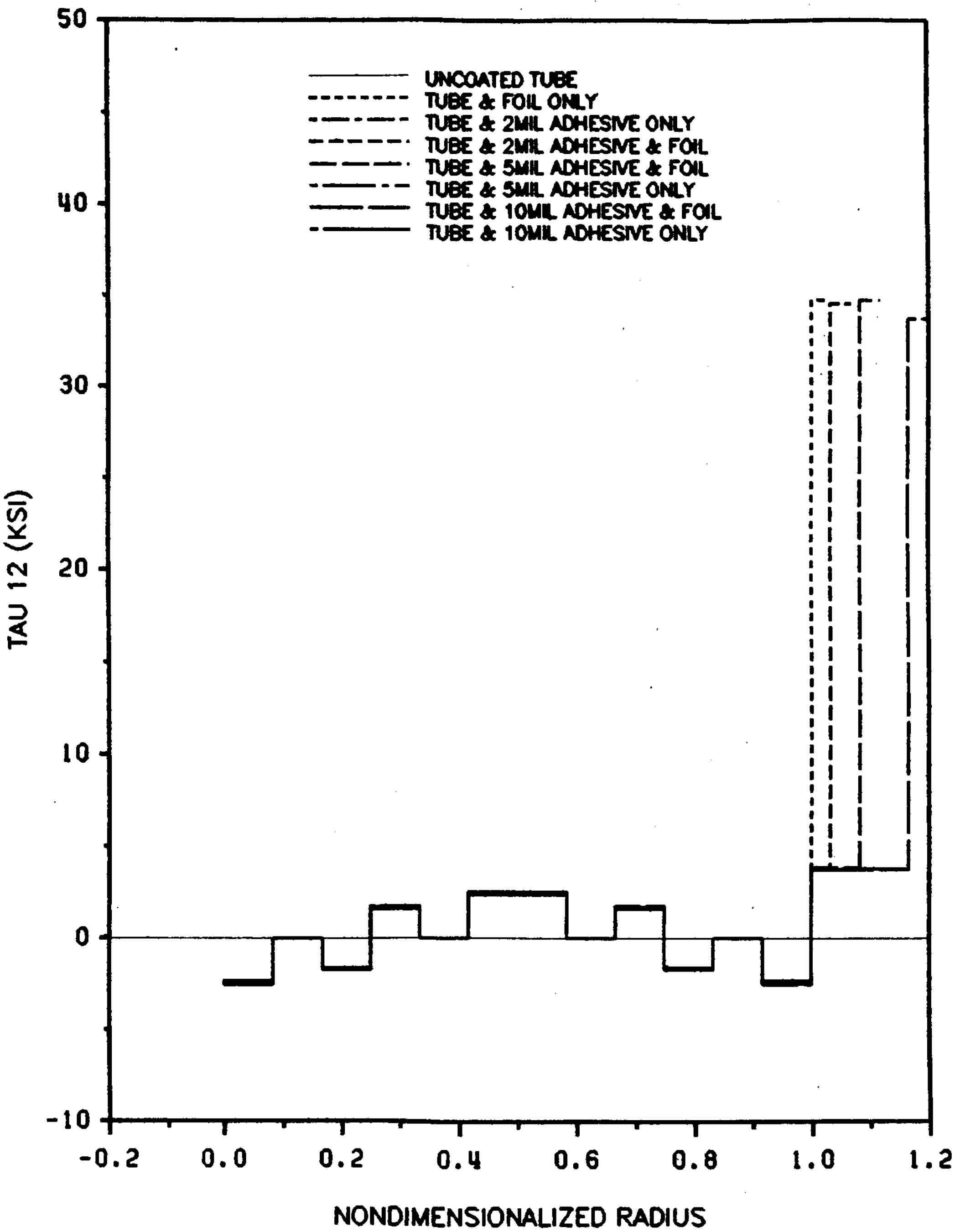

Figure 12a. Shear and Maximum Shear Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

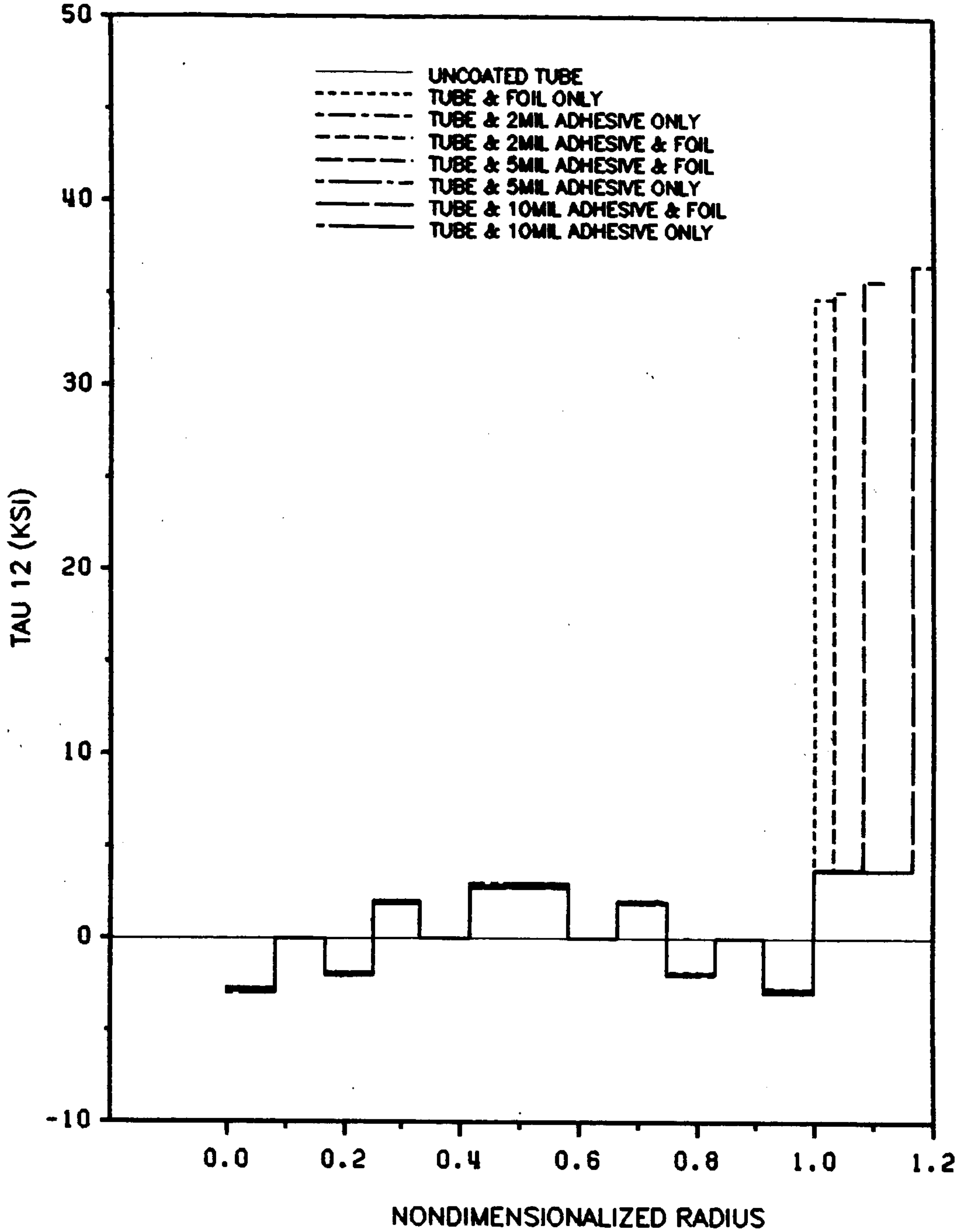

Figure 12b. Shear and Maximum Shear Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

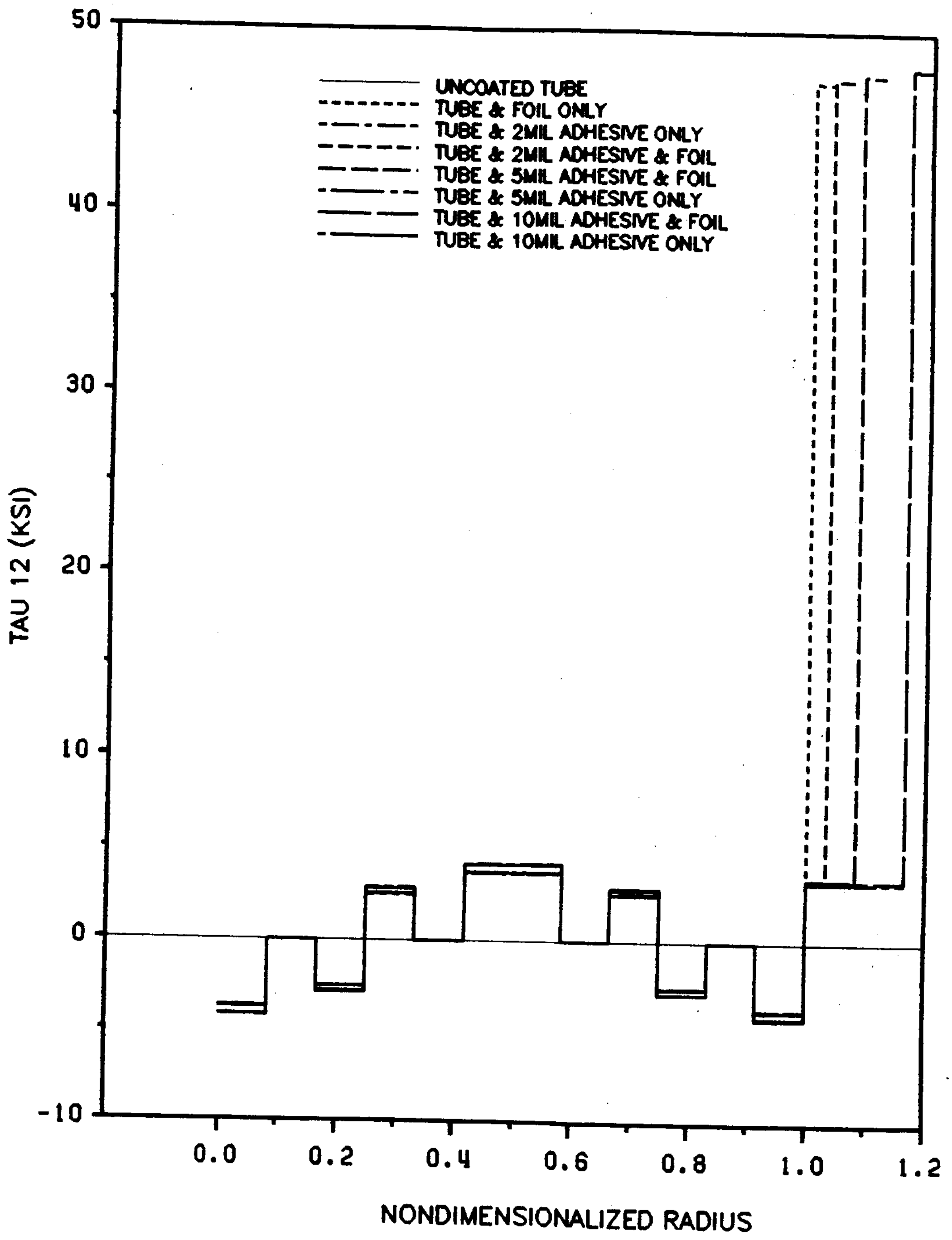

Figure 12c. Shear and Maximum Shear Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

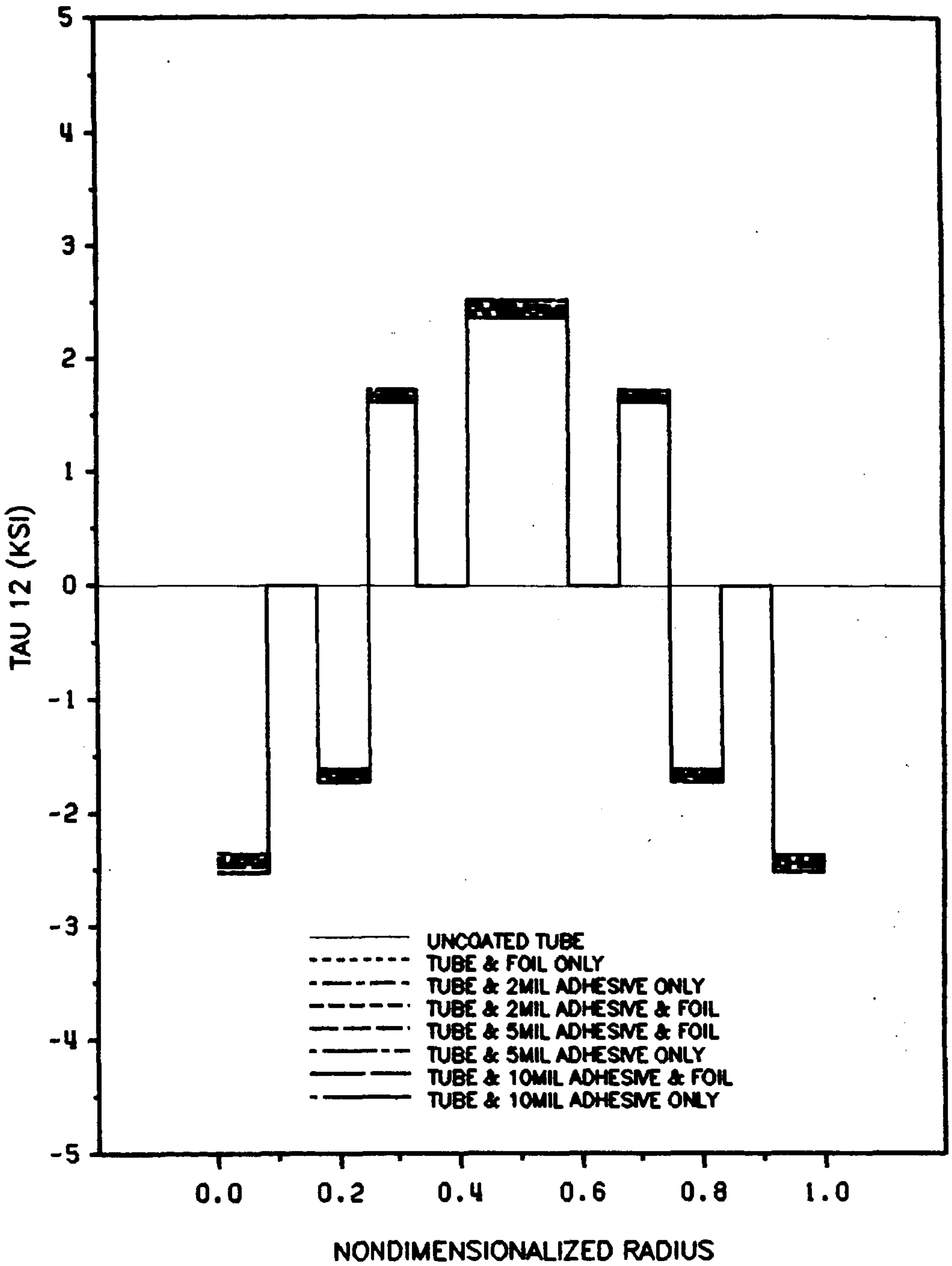

Figure 13a. Details of Shear Stresses in the T300/934 Tube at -150° F: Coatings on Outer Surface Only.

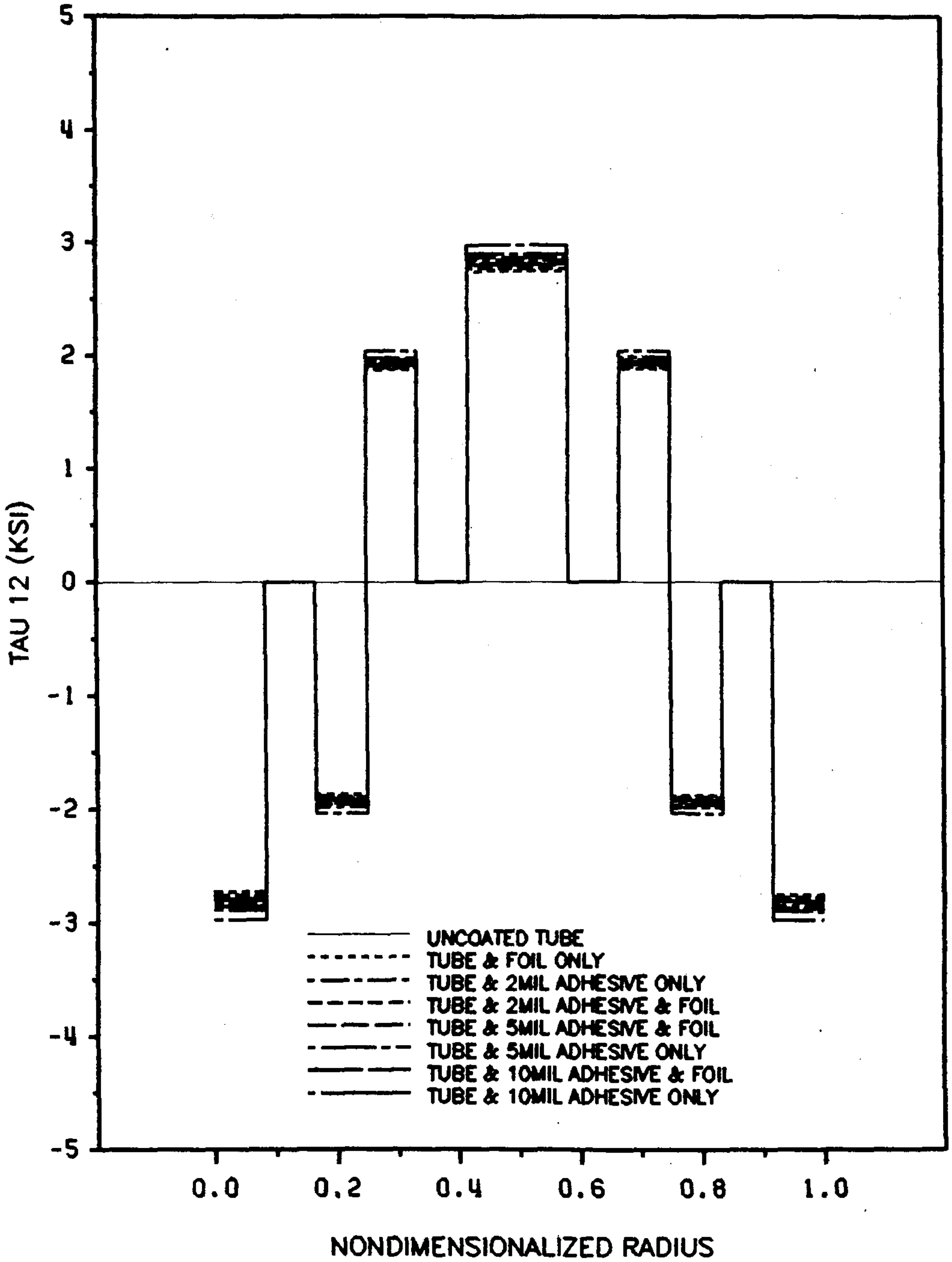

Figure 13b. Details of Shear Stresses in the P75s/934 Tube at -150° F: Coatings on Outer Surface Only.

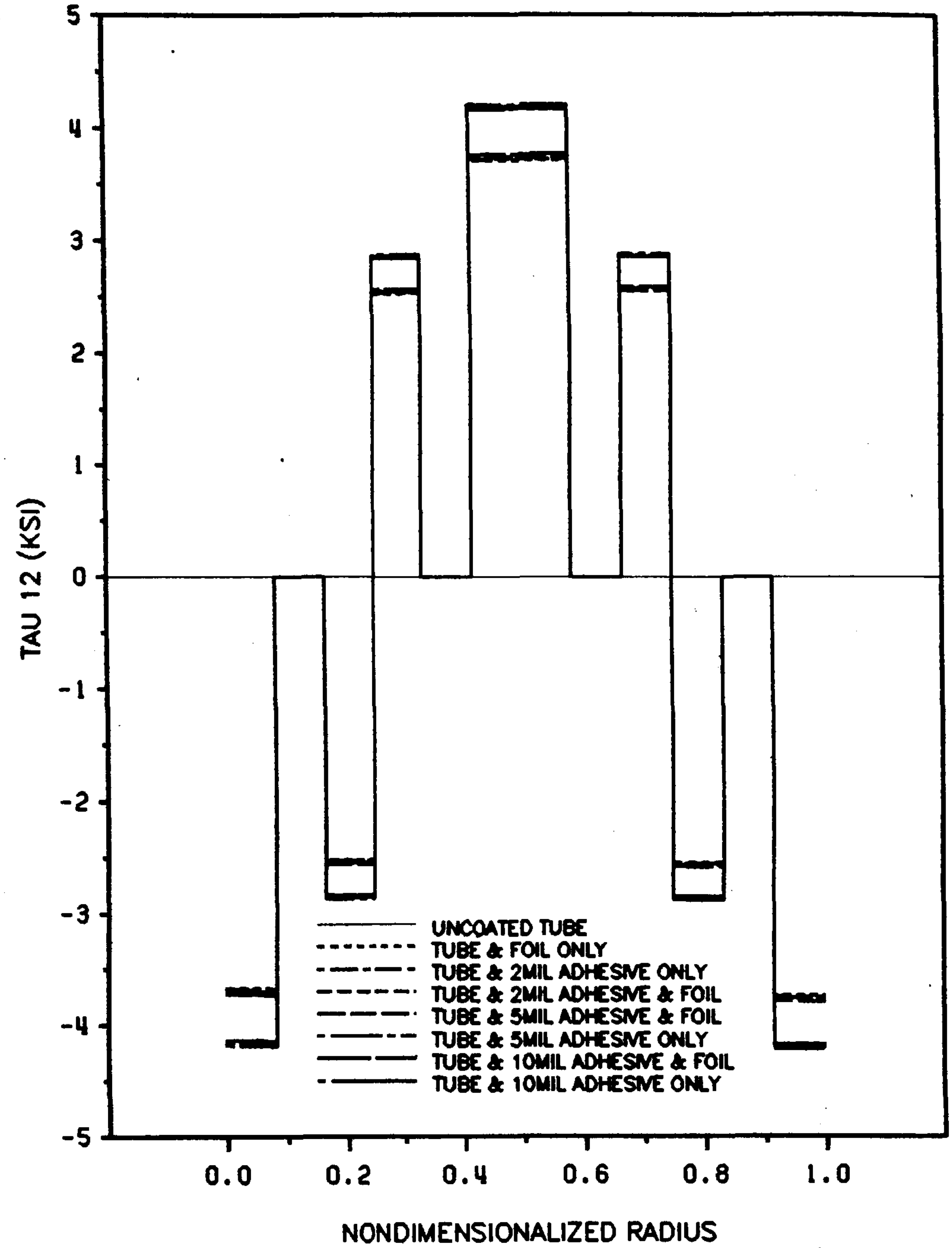

Figure 13c. Details of Shear Stresses in the P75s/BP907 Tube at -150° F: Coatings on Outer Surface Only.

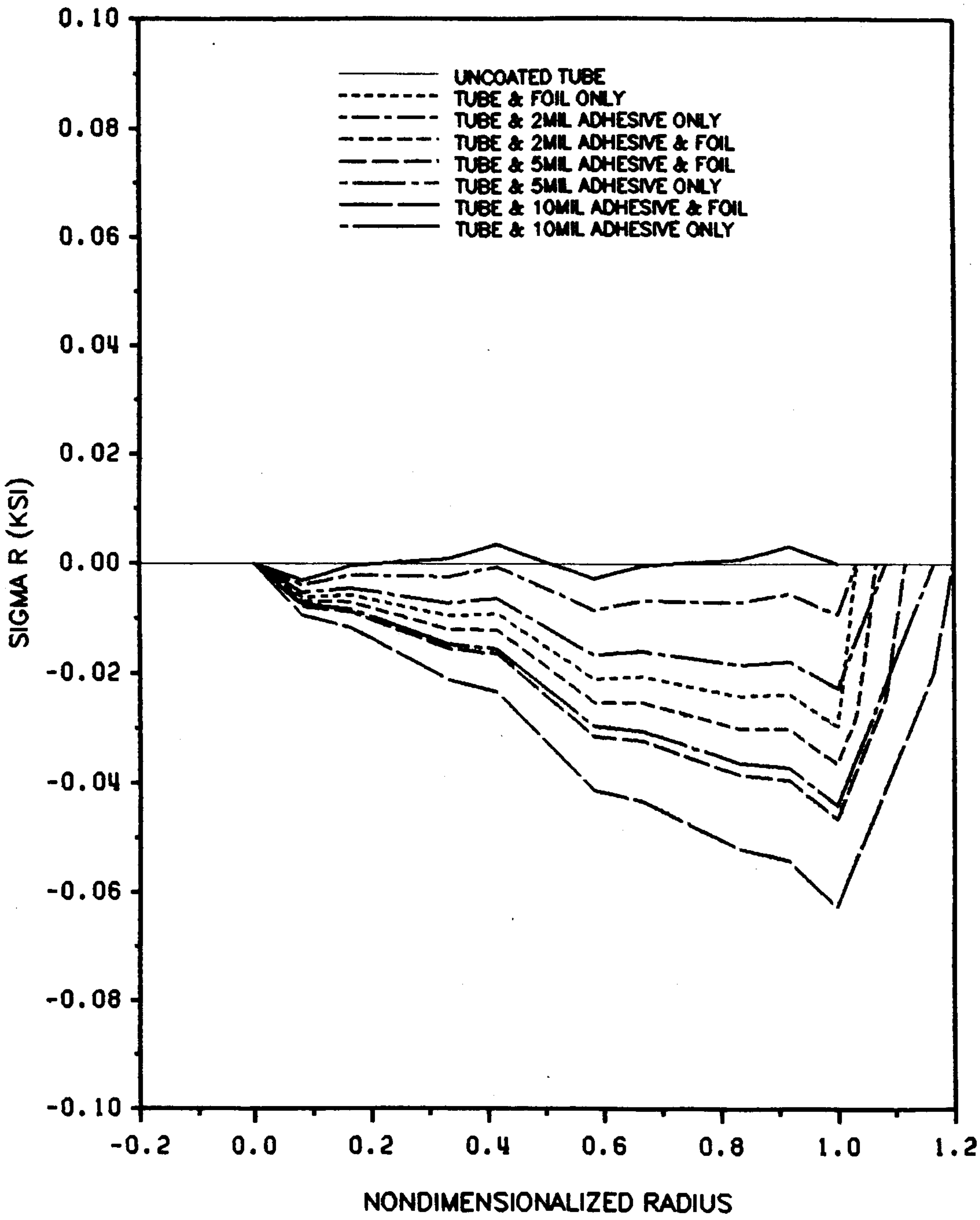

Figure 14a. Radial Stresses in the T300/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

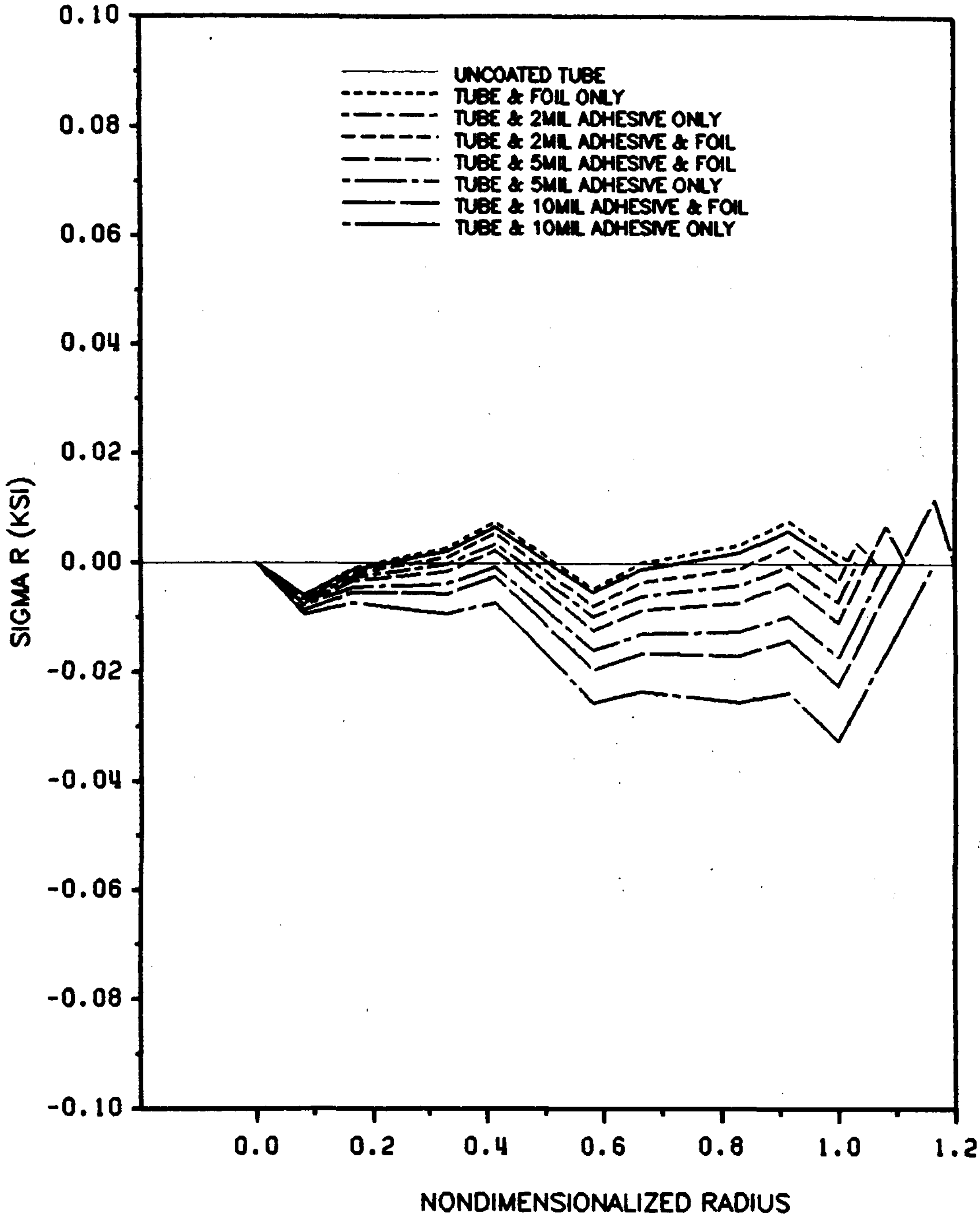

Figure 14b. Radial Stresses in the P75s/934 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

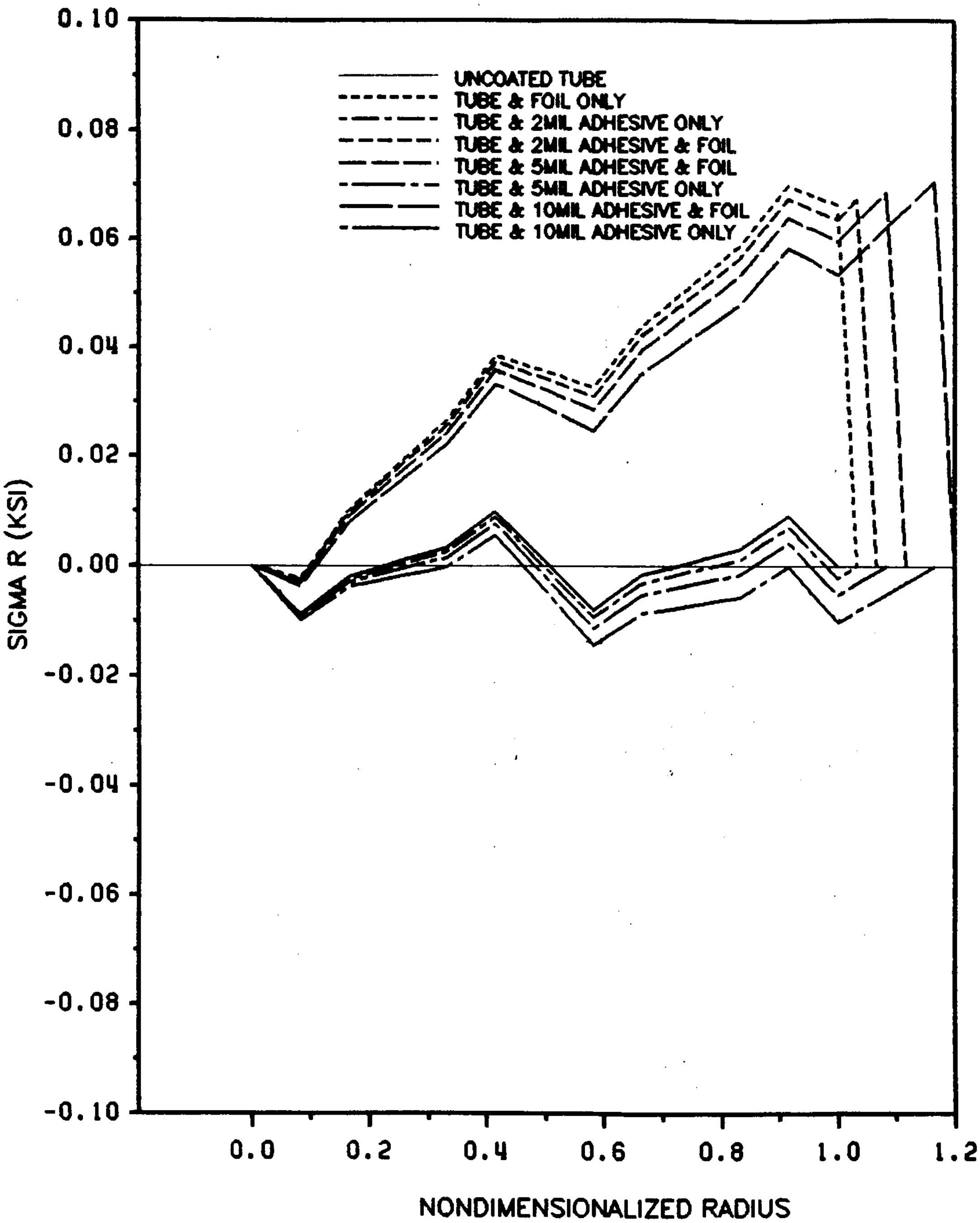

Figure 14c. Radial Stresses in the P75s/BP907 Tube, Adhesive, and Foil at -150° F: Coatings on Outer Surface Only.

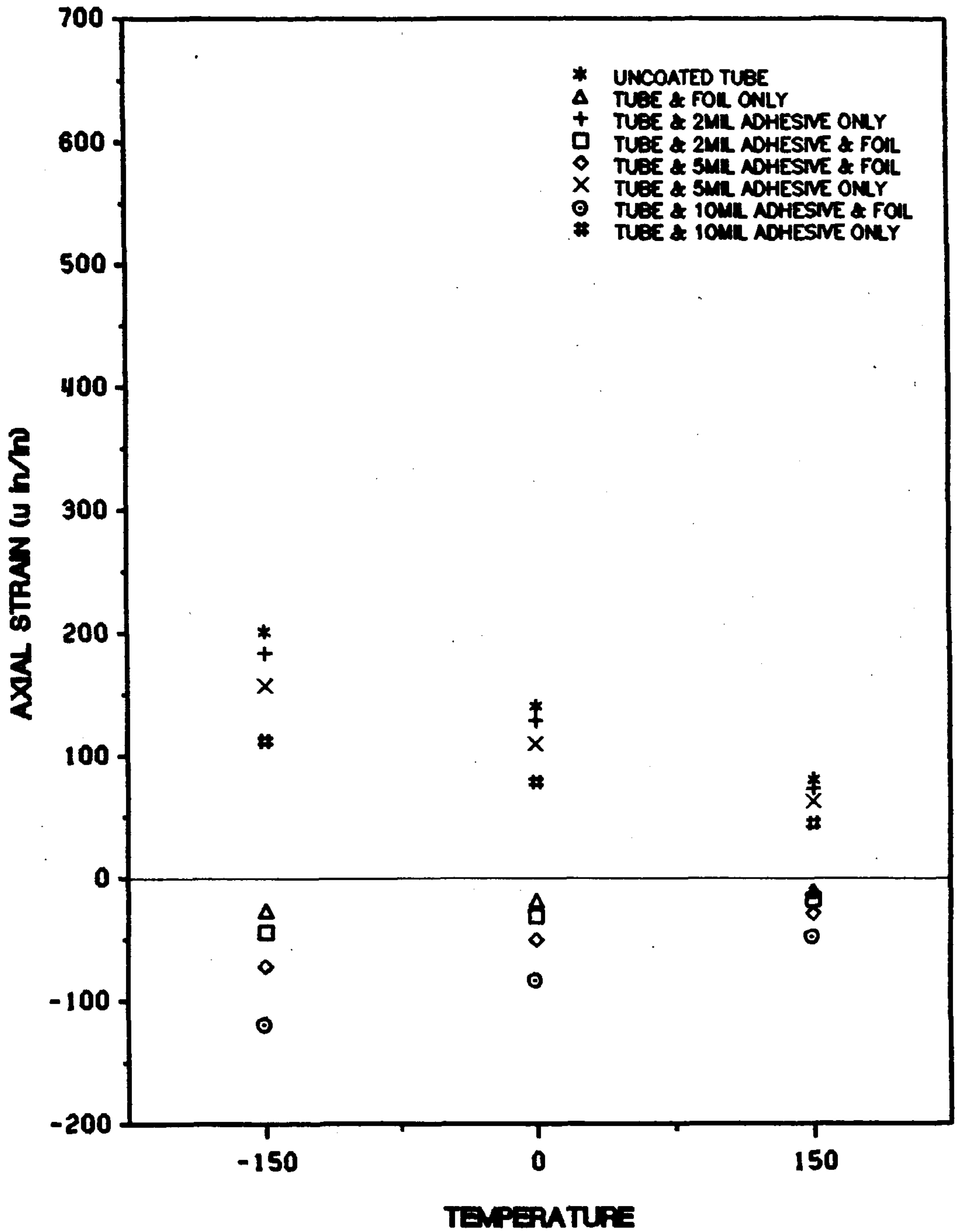

Figure 15a. Axial Extension of the T300/934 Tube: Coatings on Inner and Outer Surfaces.

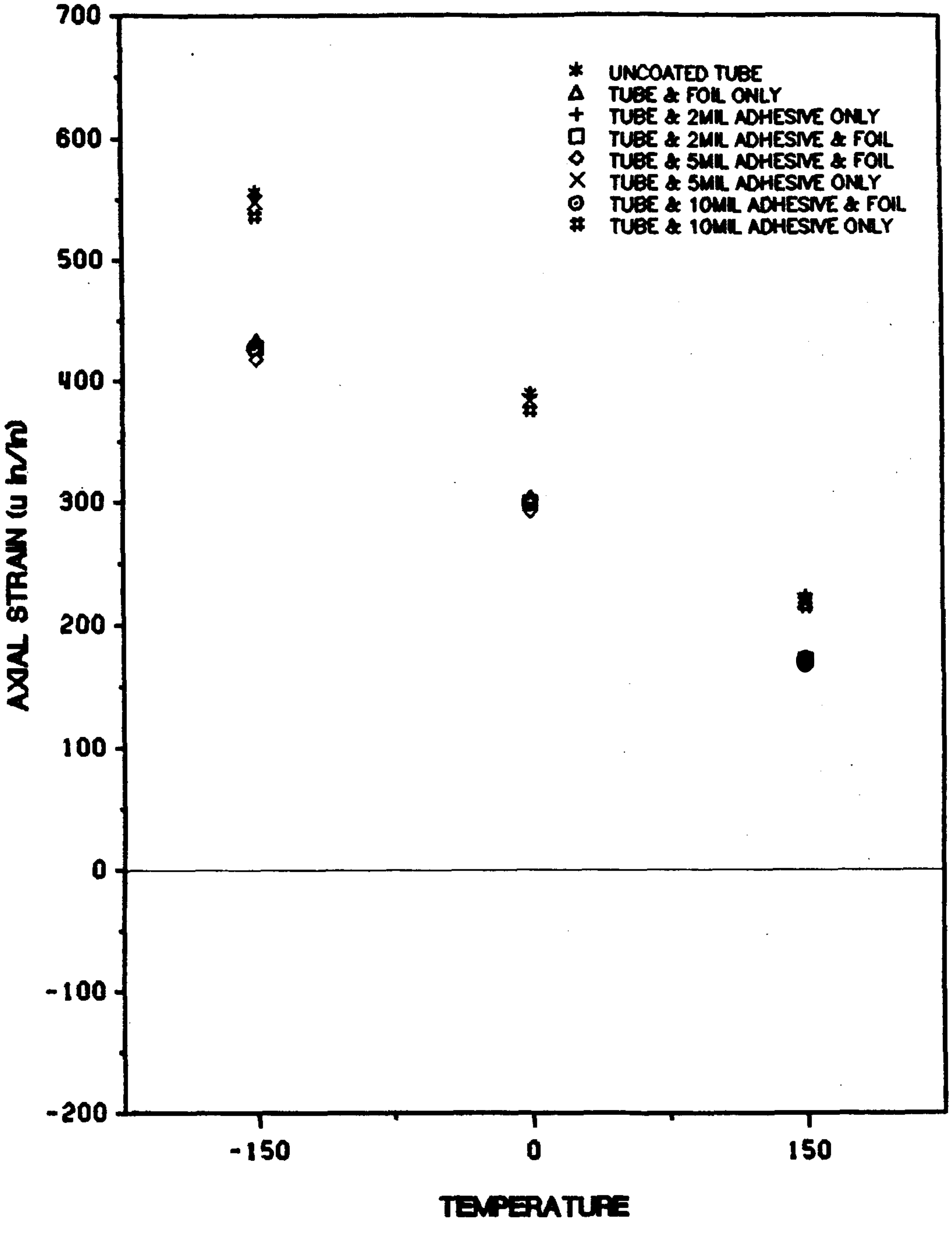

Figure 15b. Axial Extension of the P75s/934 Tube: Coatings on Inner and Outer Surfaces.

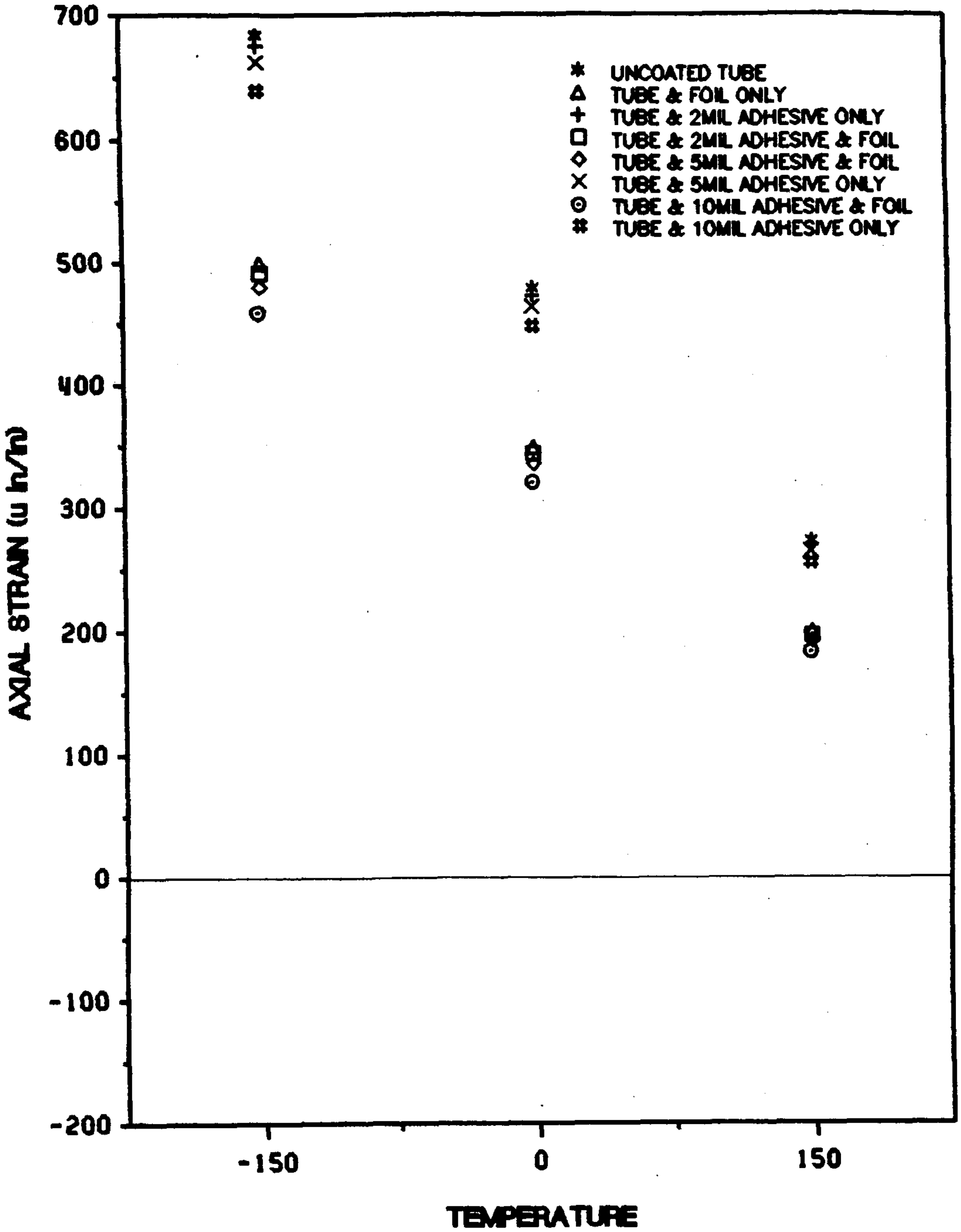

Figure 15c. Axial Extension of the P75s/BP907 Tube: Coatings on Inner and Outer Surfaces.

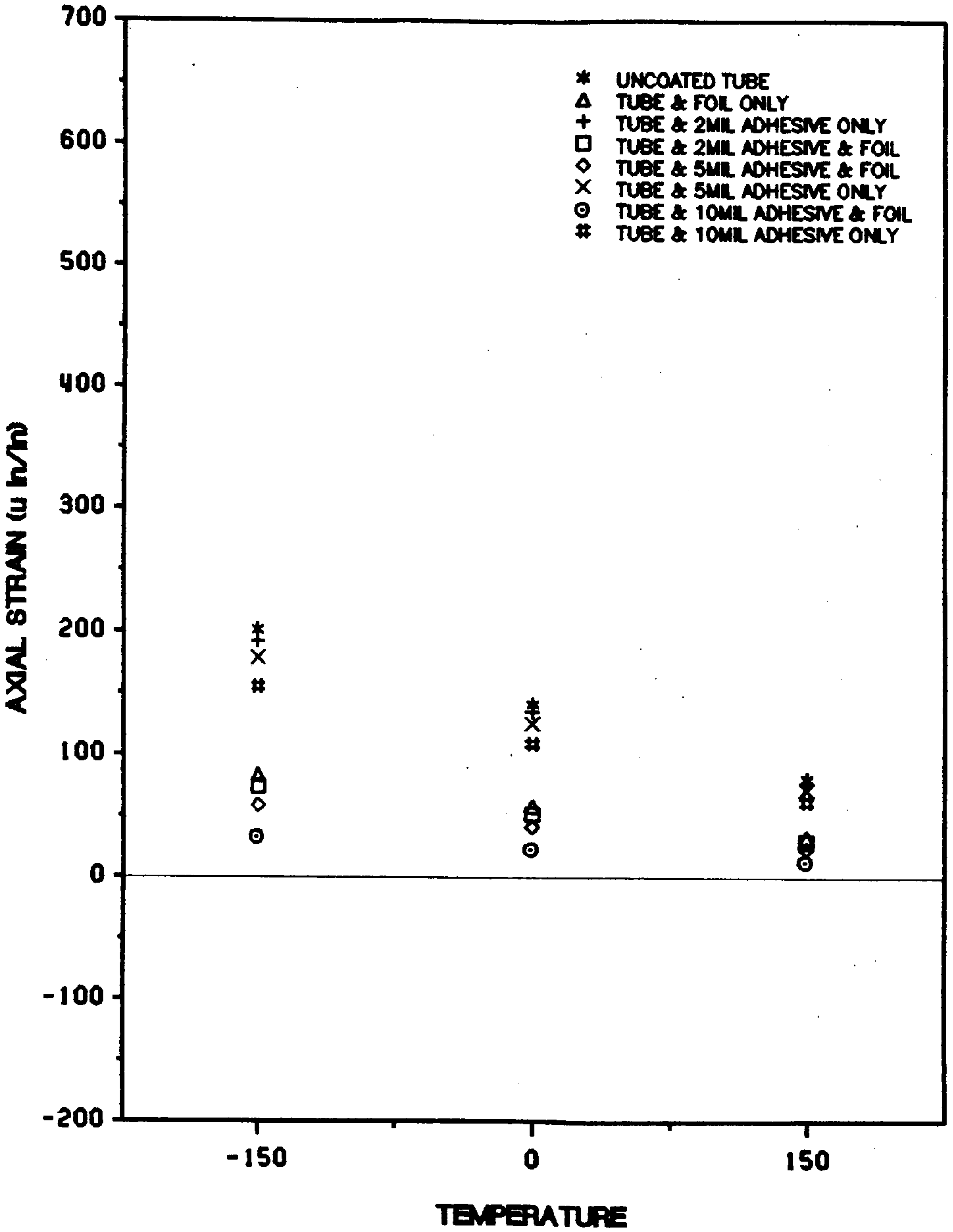

Figure 16a. Axial Extension of the T300/934 Tube: Coatings on Outer Surface Only.

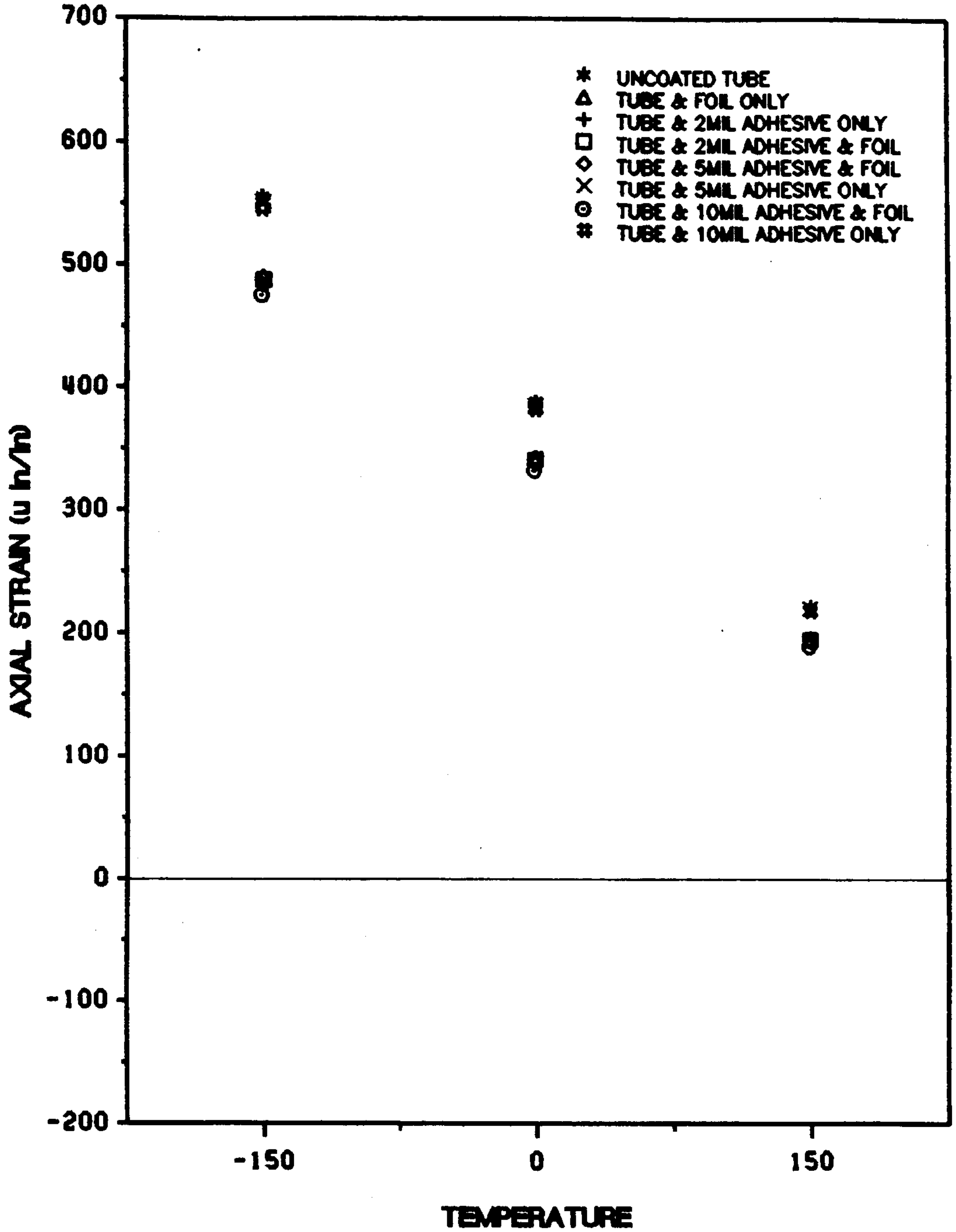

Figure 16b. Axial Extension of the P75s/934 Tube: Coatings on Outer Surface Only.

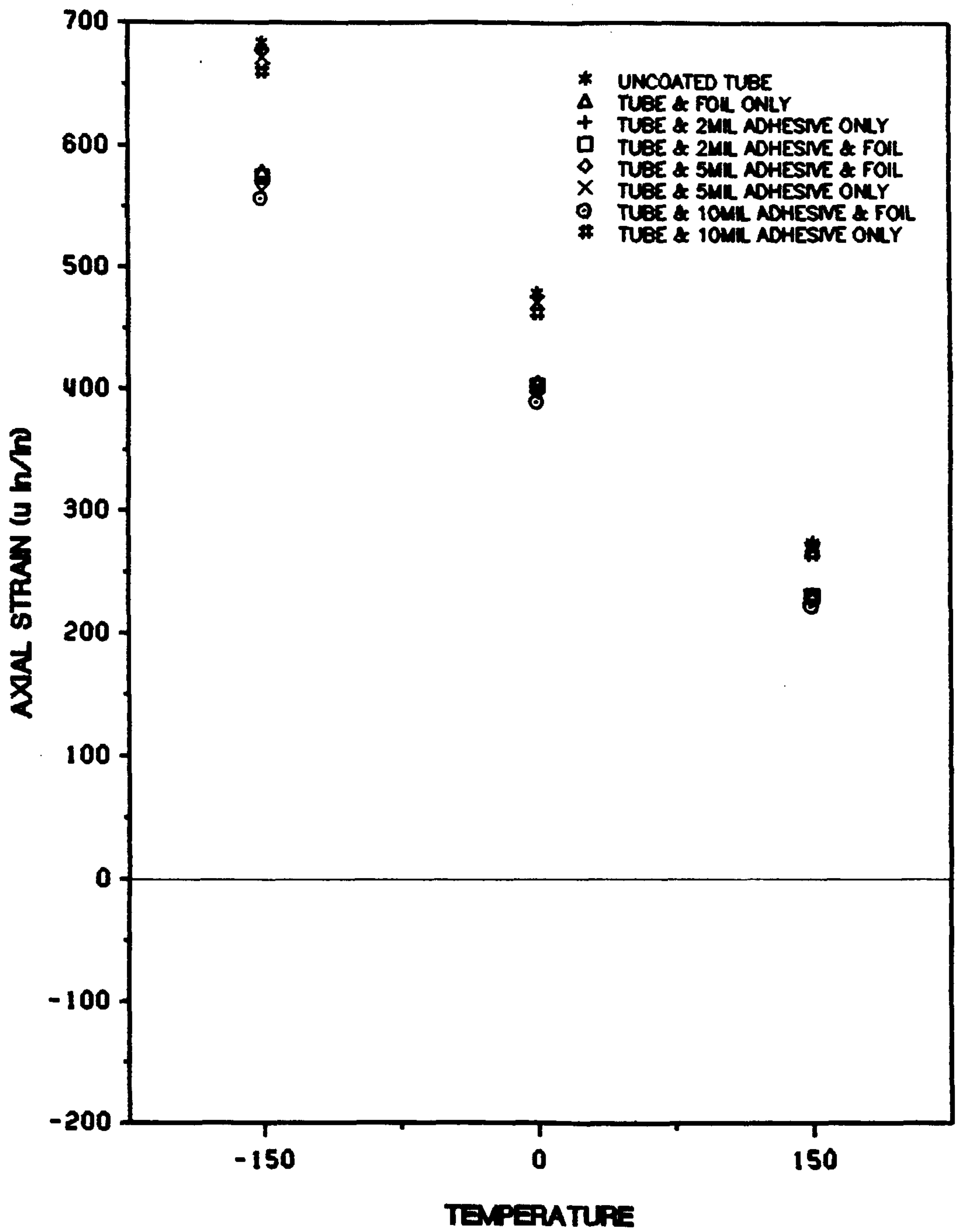

Figure 16c. Axial Extension of the P75s/BP907 Tube: Coatings on Outer Surface Only.

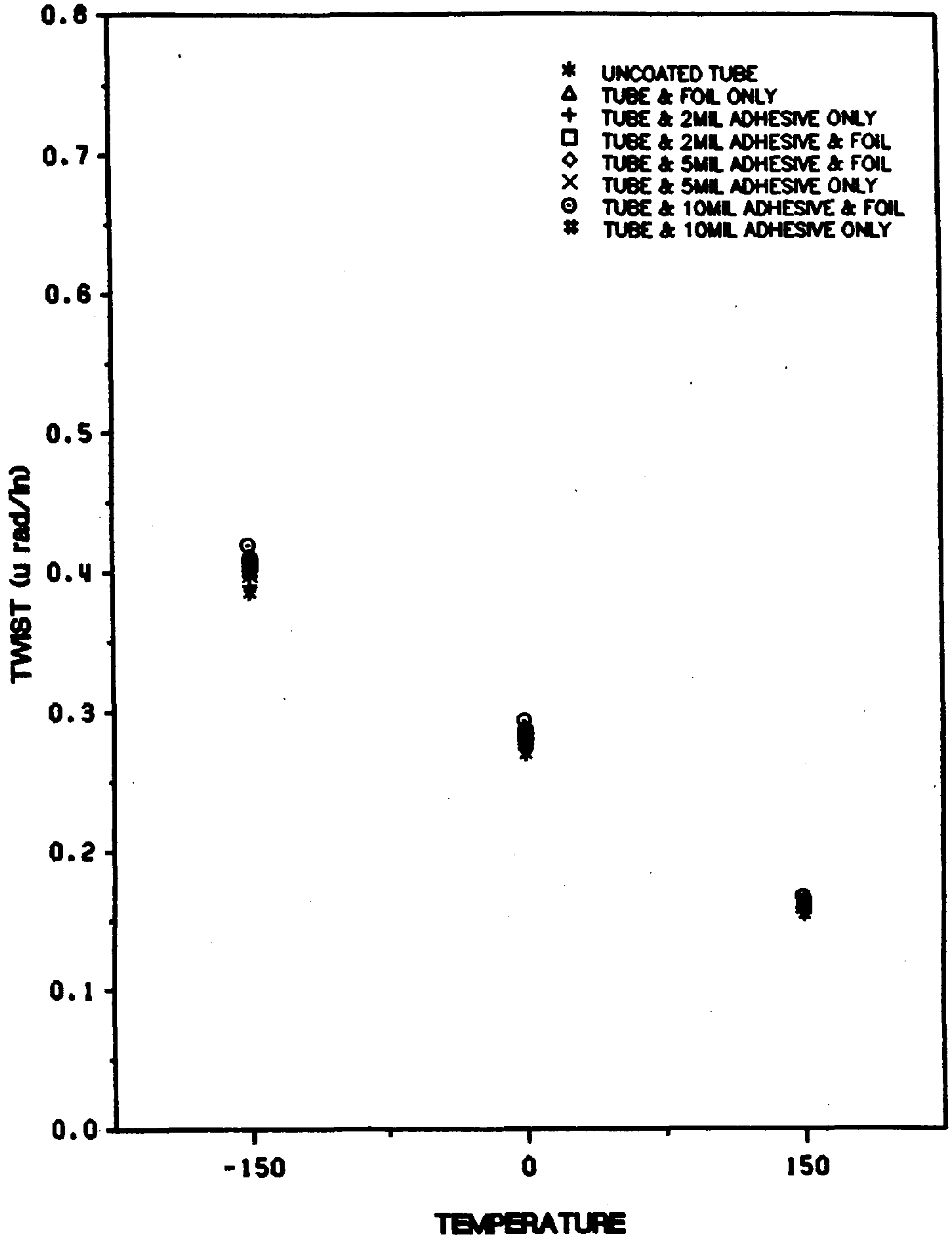

Figure 17a. Twist of the T300/934 Tube: Coatings on Inner and Outer Surfaces.

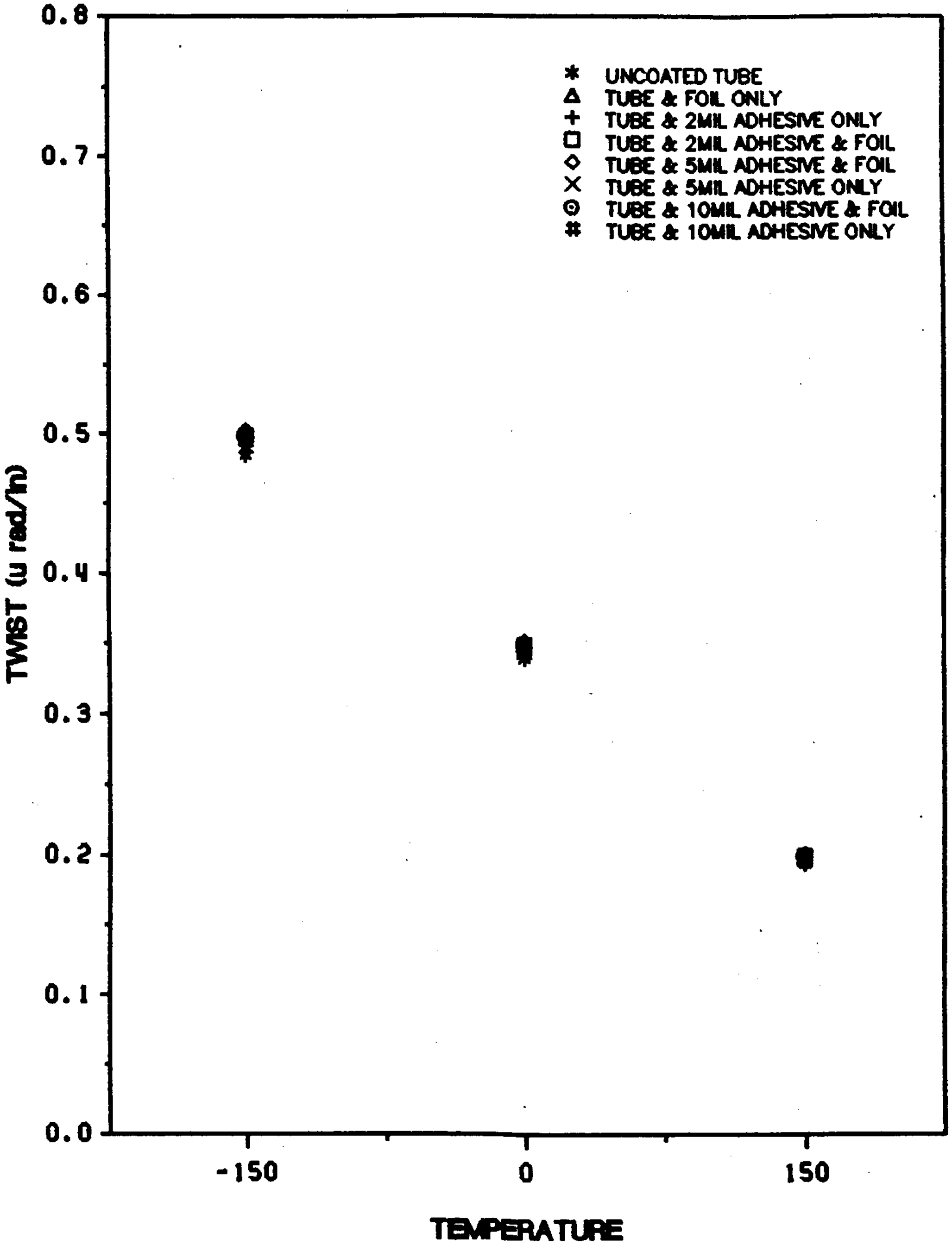

Figure 17b. Twist of the P75s/934 Tube: Coatings on Inner and Outer Surfaces.

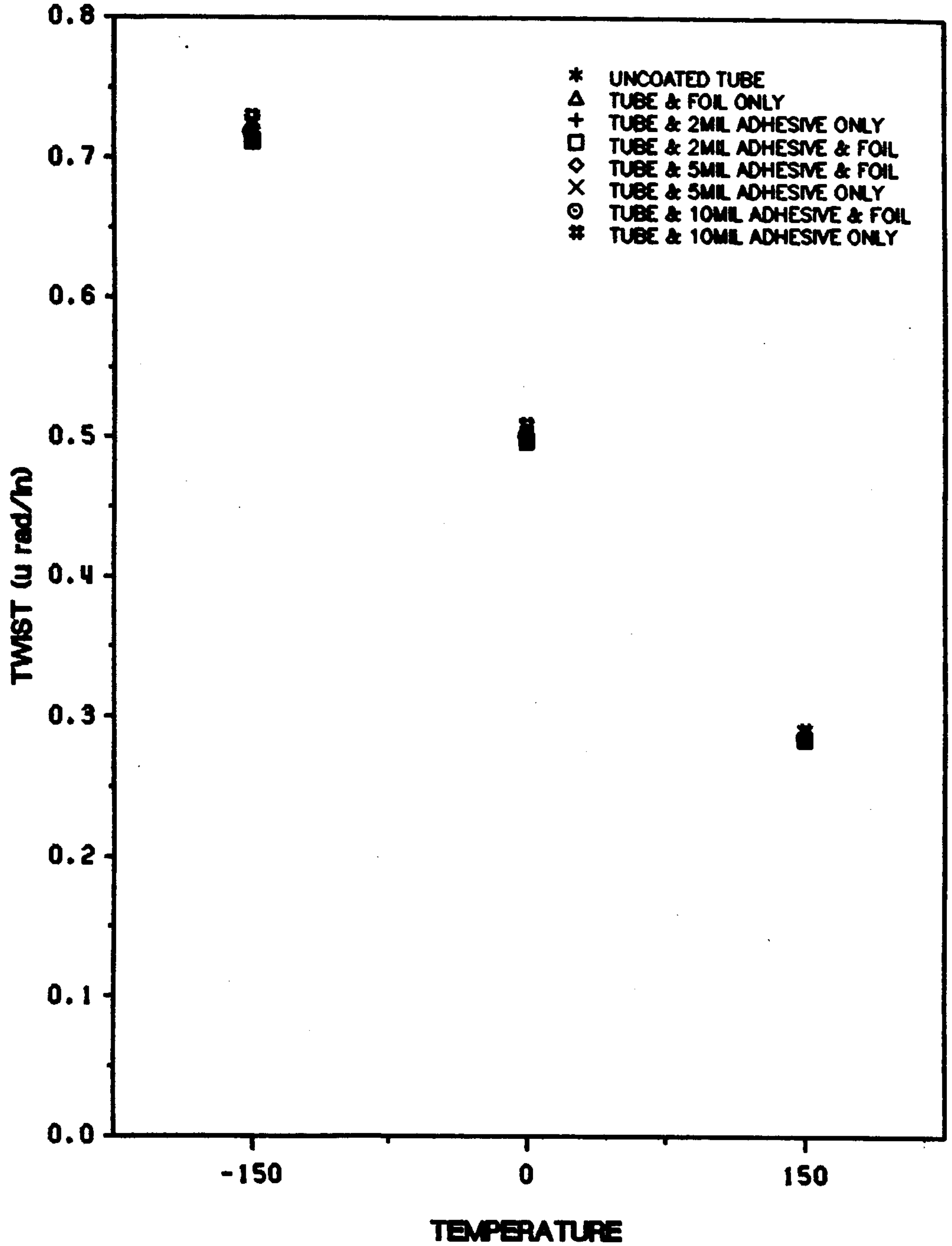

Figure 17c. Twist of the P75s/BP907 Tube: Coatings on Inner and Outer Surfaces.

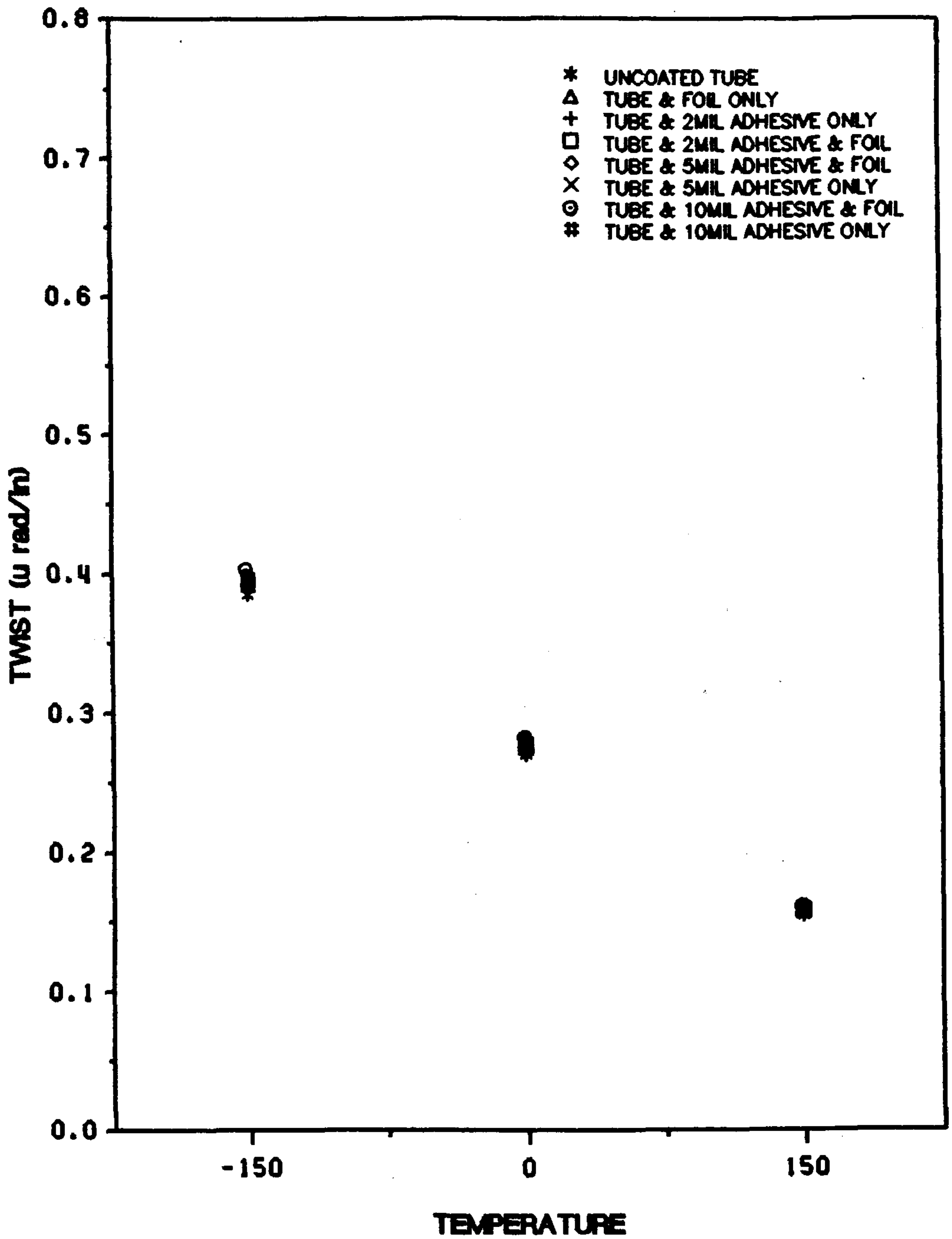

Figure 18a. Twist of the T300/934 Tube: Coatings on Outer Surface Only.

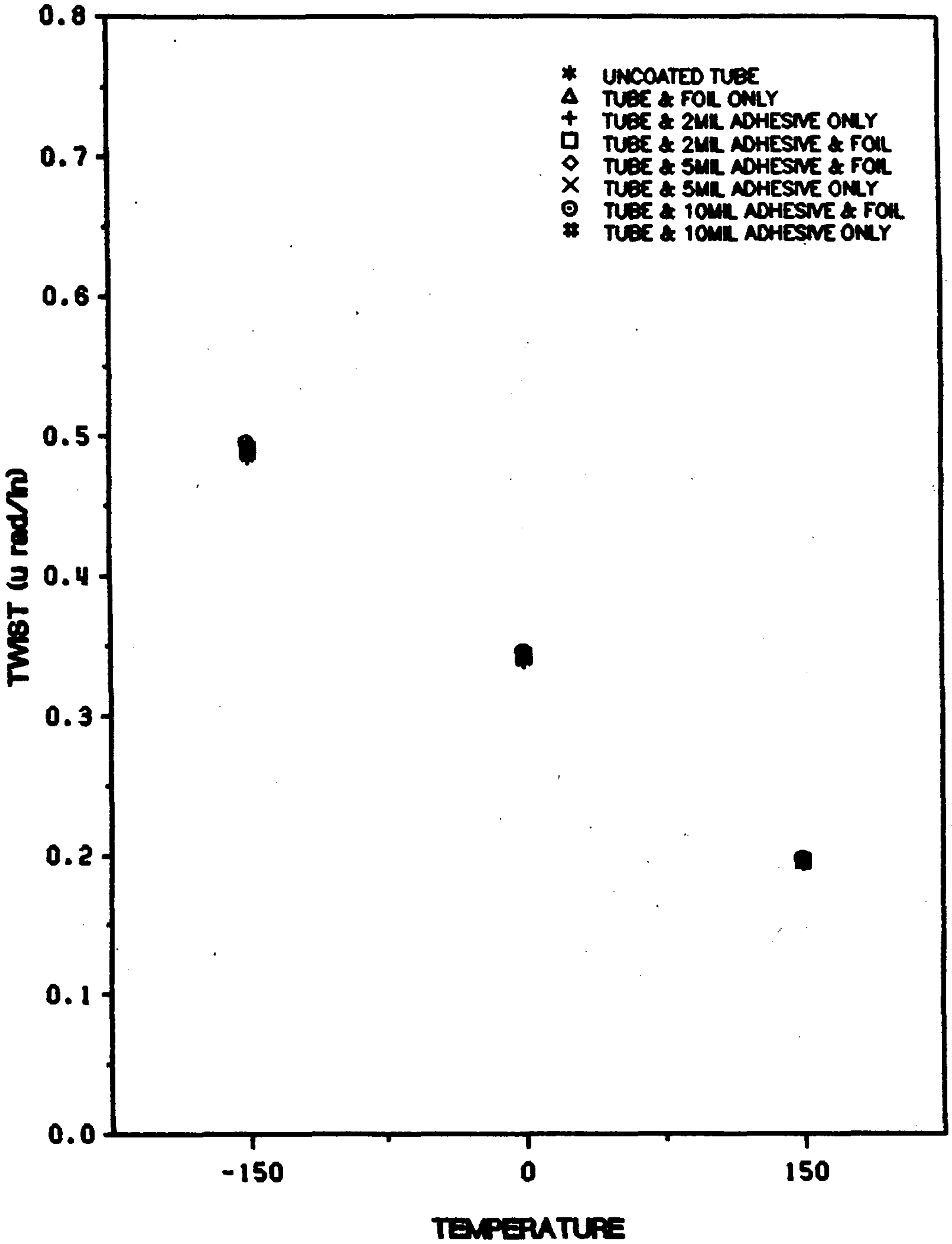

Figure 18b. Twist of the P75s/934 Tube: Coatings on Outer Surface Only.

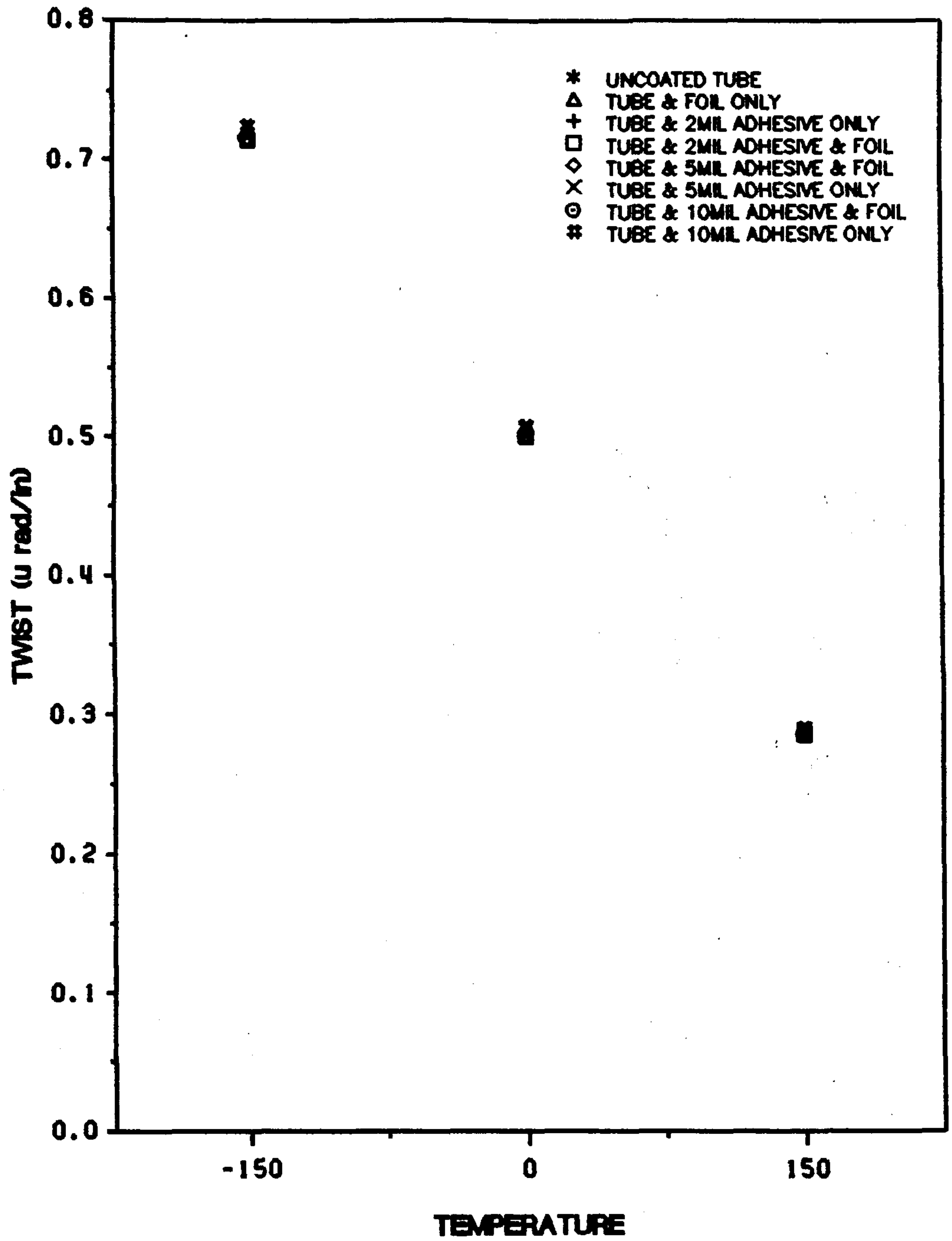

Figure 18c. Twist of the P75s/BP907 Tube: Coatings on Outer Surface Only.

VIRGINIA TECH CENTER FOR COMPOSITE MATERIALS AND STRUCTURES

The Center for Composite Materials and Structures is a coordinating organization for research and educational activity at Virginia Tech. The Center was formed in 1982 to encourage and promote continued advances in composite materials and composite structures. Those advances will be made from the base of individual accomplishments of the forty members who represent ten different departments in two colleges.

The Center functions through an Administrative Board which is elected yearly and a Director who is elected for a three-year term. The general purposes of the Center include:

- collection and dissemination of information about composites activities at Virginia Tech,
- contact point for other organizations and individuals,
- mechanism for collective educational and research pursuits,
- forum and agency for internal interactions at Virginia Tech.

The Center for Composite Materials and Structures is supported by a vigorous program of activity at Virginia Tech that has developed since 1963. Research expenditures for investigation of composite materials and structures total well over seven million dollars with yearly expenditures presently approximating two million dollars.

Research is conducted in a wide variety of areas including design and analysis of composite materials and composite structures, chemistry of materials and surfaces, characterization of material properties, development of new material systems, and relations between damage and response of composites. Extensive laboratories are available for mechanical testing, nondestructive testing and evaluation, stress analysis, polymer synthesis and characterization, material surface characterization, component fabrication, and other specialties.

Educational activities include eight formal courses offered at the undergraduate and graduate levels dealing with the physics, chemistry, mechanics, and design of composite materials and structures. As of 1984, some 43 Doctoral and 53 Master's students have completed graduate programs and several hundred Bachelor-level students have been trained in various aspects of composite materials and structures. A significant number of graduates are now active in industry and government.

Various Center faculty are internationally recognized for their leadership in composite materials and composite structures through books, lectures, workshops, professional society activities, and research papers.

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